Microscale evidence of liquefaction and its potential triggers during soft-bed deformation within subglacial traction tills

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Highlights:

Subglacial traction tills undergo repeated phases of liquefaction and deformation

This process lowers the shear strength of the till, facilitating glacier movement

This soft-bed sliding occurs in a series of 'stick-slip' events

Soft-bed sliding may be partially facilitated by glacier seismic activity

Abstract

Published conceptual models argue that much of the forward motion of modern and ancient glaciers is accommodated by deformation of soft-sediments within the underlying bed. At a microscale this deformation results in the development of a range of ductile and brittle structures in water-saturated sediments as they accommodate the stresses being applied by the overriding glacier. Detailed micromorphological studies of subglacial traction tills reveal that these polydeformed sediments may also contain evidence of having undergone repeated phases of liquefaction followed by solid-state shear deformation. This spatially and temporally restricted liquefaction of subglacial traction tills lowers the shear strength of the sediment and promotes the formation of "transient mobile zones" within the bed, which accommodate the shear imposed by the overriding ice. This process of soft-bed sliding, alternating with bed deformation, facilitates glacier movement by way of 'stick-slip' events. The various controls on the slip events have previously been identified as: (i) the introduction of pressurised meltwater into the bed, a process limited by the porosity and permeability of the till; and (ii) pressurisation of porewater as a result of subglacial deformation; to

which we include (iii) episodic liquefaction of water-saturated subglacial traction tills in response to glacier seismic activity (icequakes), which are increasingly being recognized as significant processes in modern glaciers and ice sheets. As liquefaction operates only in materials already at very low values of effective stress, its process-form signatures are likely indicative of glacier sub-marginal tills.

1. Introduction

Deformation of the soft, unconsolidated sediments occurring beneath many glaciers is thought to account for a substantial component of their forward motion (e.g. Alley *et al*., 1986; Boulton and Hindmarsh, 1987; Clarke, 1987; Alley *et al*., 1987a, b; Alley, 1989a, b; Humphrey *et al*., 1993; Boulton et al. 2001). This concept of a "deforming bed" was first proposed following experiments carried out upon the till beneath the margin of Breiðamerkurjökull in SE Iceland (Boulton, 1979; Boulton and Hindmarsh, 1987; Boulton and Dobbie, 1998) and further supported by high resolution seismic surveys beneath Ice Stream B in Antarctica (Blankenship *et al*., 1986, 1987). Subsequent field studies and geotechnical experiments have identified a range of possible subglacial deformation responses to glacier basal shear stresses which give rise to increasing cumulative shear strain upwards through the till profile towards the ice base (Boulton *et al*., 1974; Boulton and Jones; 1979; Boulton, 1986; Hindmarsh, 1997; Tulaczyk *et al*., 2000a, b; Kavanaugh and Clarke, 2006). The water content, lithological composition and thickness of the tills, along with temporal and spatial changes in the porewater pressures that occur within the subglacial environment, are all considered to exert a strong control on the style and intensity of deformation (see Evans *et al*., 2006 and references therein). However, the exact nature of the response of tills during subglacial deformation remains a subject of significant debate (cf. Boulton and Hindmarsh, 1987; Benn and Evans, 1996; Boulton 1996; Hindmarsh, 1997; Murray, 1997; Piotrowski and Kraus; 1997; Piotrowski *et al*., 1997; Tulaczyk, 1999; Fuller and Murray, 2000; Tulaczyk *et al*., 2000a, b; van der Meer *et al*., 2003; Piotrowski *et al*., 2004, 2006; Kavanaugh and Clarke, 2006; Evans *et al*., 2006; Damsgaard *et al*., 2016), especially the responses that are likely to arise through changing water pressures. For example a number of studies of marine terminating ice streams in West Antarctic have suggested that tidal movements effecting the floating part of the glacier can influence the upstream distribution of pore water pressure leading to variations in the velocity of ice flow (e.g. Winberry *et al*., 2011; Walker *et al*., 2013; Thompson *et al*., 2014; Rosier *et al*., 2015).

Boreholes through the Trapridge Glacier (NW Canada) indicate that subglacial deformation is driven by changes in shear stress due to the variation in ice-bed coupling and water pressure as well as possible changes in deforming layer thickness (Blake, 1992; Blake *et al*., 1992; Kavanaugh and

Clarke, 2006). Iverson *et al*. (1994, 1995) used investigations at Storglaciären in northern Sweden to emphasize the complexity of subglacial deformation, concluding that the till acts as a "lubricant" with forward motion being dominated by basal sliding and ploughing of large clasts embedded in the base of the ice. Some subglacial experiments have revealed that, instead of increasing coupling at the ice-bed interface, ploughing clasts actually weaken sediment by elevating porewater pressures (PWP) in sediment prows (Iverson *et al*., 1994; Iverson, 1999; Fischer *et al*., 2001; Iverson, 2010). Hindmarsh (1996) suggested that the till itself may slide over an underlying hard substrate, giving rise to polished/striated bedrock surfaces. Similarly Truffer *et al*. (2000) and Kjær *et al*. (2006) have also argued for deformation having occurred deep within or beneath subglacial tills as a potential mechanism for rapid ice flow. Alternatively, Fuller and Murray (2000) recorded basal sliding over soft-sediments at the base of Hagafellsjökull in Iceland, associated with only a very thin (< 16 cm) layer of deformed sediment.

Reconciling these process studies with interpretations of the subglacial conditions recorded in ancient sedimentary sequences is particularly challenging, because palaeo-ice sheets and glaciers have left a legacy that comprises complex assemblages of deposits whose sedimentological and structural signatures are ambiguous. Consequently, our current understanding of the conditions encountered within the subglacial environment relies heavily upon theoretical models stemming from a modest number of glaciological process case studies and laboratory experiments. From this comes an understanding that increased porewater pressure (PWP) within the glacier bed, when it is at steady state consolidation, results in the "dilation" of the sediment and a fall in its shear strength (Fig. 1). Fluctuations in PWP will lead to repeated phases of "dilation" followed by "collapse" as the water pressure falls, the latter leading to an increase in the shear strength of the sediment (also see Damsgaard *et al*., 2016; Winberry *et al*., 2011); this response may be dampened by materials with lower diffusivity (Iverson, 2010). The computer simulations of the deformation of subglacial tills by Damsgaard *et al*. (2016) have demonstrated that creep in these modelled simple granular materials keeps porosities somewhat elevated between failure events. At the highest values of PWP the ice may become decoupled from its bed and there may be a significant fall in the shear stress translated to the underlying sediments, effectively switching off subglacial deformation and promoting basal sliding as the dominant mechanism of glacier forward motion. This stick-slip style of motion operating in soft glacier beds has been reported by Fischer and Clarke (1997) and Fischer *et al.* (1999) for the Trapridge Glacier, where decoupling of the ice takes place during periods of high water pressure. Boulton *et al.* (2001) also propose a stick-slip motion, operating diurnally, to explain their observations at Breiðamerkurjökull, Iceland, where rising water pressures initiate till dilation, followed by the reduction in ice-bed friction and then ice-till decoupling. Falling water pressures then return the till to a deforming state and re-couple the ice-bed interface; a continued fall in water pressure below the threshold for failure causes the bed to stick and enhanced ice-bed traction. However, dilation increases the connectivity between intergranular pore spaces, temporarily increasing the permeability of the till promoting the dewatering of the sediment and dilatory arrest (Youd, 2003) or dilatant hardening (Iverson *et al*., 1998; Moore and Iverson, 2002; Damsgaard *et al*., 2015). Consequently repeated phases of till dilation, in the absence of a mechanism to reintroduce water into these subglacial sediments, will cause an increase in ice-bed friction.

The above case studies notwithstanding, some significant uncertainties still exist in our understanding of till deformation processes and forms including: the spatial and temporal patterns of subglacial deformation, the variability of subglacial sediment rheology, and the inter-relationships of sediment deformation and subglacial hydrology, as well as the inter-relationships between sliding over soft-sediments with bed deformation. Given the constraints inherent within the discoveries outlined above, we should expect all subglacial tills to show at least some evidence of deformation. However, the massive nature of many subglacial tills exposed at the margins of contemporary glaciers and in the geological record has been used to question the pervasive nature of deformation, at least at the macroscale, even though shear-induced mixing has been invoked to explain such massive appearances (Piotrowski and Tulaczyk, 1999; Hooyer and Iverson, 2000). Due to this macroscopically massive nature of many tills, micromorphology is increasingly being used in the analysis of subglacial sediments (see Menzies and Maltman, 1992; van der Meer, 1993; Menzies *et al*., 1997; Khatwa and Tulaczyk, 2001; van der Meer *et al*., 2003; Roberts and Hart, 2005; Hiemstra *et al*., 2005; Baroni and Fasano, 2006; Larsen *et al*., 2006, 2007; Phillips *et al*., 2011; Neudorf *et al*., 2013; Spagnolo *et al*., 2016). In particular, this approach has been used to unravel the complex deformation histories recorded by glacigenic sequences (van der Meer, 1993; Phillips and Auton, 2000; van der Wateren *et al*., 2000; Menzies, 2000; Phillips *et al*., 2007; Lee and Phillips, 2008; Denis *et al*., 2010; Vaughan-Hirsch *et al*., 2013; Narloch *et al*., 2012, 2013) as well as to investigate the role played by pressurised meltwater during deformation events (Hiemstra and van der Meer, 1997; Phillips and Merritt, 2008; van der Meer *et al*., 2009; Denis *et al*., 2010; Phillips *et al*., 2013a, b; Narloch *et al*., 2012, 2013). The development of a quantitative microstructural mapping technique (Phillips *et al*., 2011) has the potential to increase our understanding of subglacial processes by highlighting the relationships between the various microstructures developed within tills, thereby allowing a detailed relative chronology of events to be established.

This paper presents the results of a number of detailed micromorphological and microstructural studies carried out on subglacial tills and identifies significant structures indicative of liquefaction events during till production. It is argued that this evidence is entirely consistent with the stick-slip processes that appear to be operating during soft-bed sliding/ploughing (Brown *et al*., 1987; Tulaczyk *et al*., 2001; Clark *et al*., 2003; Podolskiy and Walter, 2016) and, moreover, could record the impacts of glacier seismic activity that are now widely reported from modern glacier and ice sheet systems.

2. Microscale evidence of subglacial deformation processes and liquefaction (Scotland and Switzerland case studies)

Intensive micromorphological analyses of the subglacial traction tills from two case studies are here reported as examples of subglacial process-form products from one lowland (Nairn, Scotland) and one upland (Galmis, Switzerland) setting. Previous investigations at both locations have demonstrated the subglacial genesis of the tills and hence we concentrate here on the microscale evidence for the interactions between bed shearing and porewater fluctuations.

Figure 2 shows the compiled results of a micromorphological study of subglacial traction tills exposed at a number of sites in the Nairn area of NE Scotland (Fig. 3). All the sites occur to the north of the Cairngorm plateau and comprise a sequence of brown sandy and silty tills (up to 10 m thick) interstratified with sands and gravels (outwash) containing a high proportion of locally-derived sedimentary, igneous and metamorphic rock fragments (Auton *et al*., 1990; Phillips *et al*., 2011; Merritt *et al*., 2017). The tills were deposited by ice flowing northwards from the Central Highlands towards the coast (Fig. 3) during the main phase of the Late Devensian (Late Weichselian; Marine Isotope Stage 2) glaciation of NE Scotland (see Auton *et al*., 1990; Phillips *et al*., 2011; Phillips *et al*., 2013; Merritt *et al*., 2017). Typical of subglacial traction tills (*sensu* Evans *et al*., 2006), the diamictons used in this study have developed in a zone of enhanced glacier bed deformation, termed the 'mobile' or 'active' layer by Evans *et al*. (2006). From hereon we use the term 'transient mobile zone' (TMZ) in order to emphasize the spatial and temporal variations in subglacial deforming bed processes proposed by a number of researchers (cf. Piotrowski and Kraus, 1997; Boyce and Eyles, 2000; van der Meer et al., 2003; Larsen *et al*., 2004, 2007; Piotrowski *et al*., 2004, 2006; Evans *et al*., 2006; Meriano and Eyles, 2009).

In thin section, the Scottish tills are composed of coarse-grained, poorly-sorted, matrix-supported, massive to weakly-stratified, sandy diamictons containing angular to subangular granule to pebble-sized rock fragments. Sand grains are mainly composed of monocrystalline quartz and subordinate amounts of feldspar which exhibit preferred shape alignments (see rose diagrams on Figs. 4 to 11). Detailed microstructural mapping of the thin sections has revealed a complex, but systematic, array of deformation fabrics developed within the diamictons (Figs. 2, 4 to 11). These are interpreted as having formed by the passive rotation of sand grains into the planes of the foliations, defining a number of clast microfabrics (Phillips *et al*., 2011). Although from different localities across NE Scotland, the tills show a remarkably similar range of microstructures (see Figs. 4 to 11) indicating that there are a number of common processes occurring during their formation, and that subglacial deformation was dominated by foliation development.

Three successive generations of microfabric of varying intensity have been identified, reflecting the heterogeneous nature of subglacial deformation (cf. Phillips *et al*., 2011). The spacing of these microfabrics is controlled by the grain size of the diamicton matrix and spatial distribution of larger clasts (Figs. 2, 4 and 5), which acted as rigid bodies during foliation development. The earliest fabric (S1) dips down-ice (purple on Figs. 2 and 4 to 11) and is either crenulated (folded) (Fig. 6) or cross-cut (Fig. 7) by a more pervasive, up-ice dipping second (S2) foliation (green on Figs. 2 and 4 to 11). Both S1 and S2 are cross-cut by a heterogeneous third (S3) fabric (dark green on Figs. 2 and 4 to 11) which is thought to record the progressive partitioning of deformation into narrow subhorizontal and down-ice dipping shear zones formed during the later stages of deformation. The geometry of the microfabrics is consistent with the formation of a conjugate set of Riedel shears (Passchier and Trouw, 1996) and subhorizontal shear foliation (Fig. 2) in response to shearing imposed by the overriding ice (cf. Phillips *et al*., 2011; Spagnolo *et al*., 2016). The orientation, geometry and kinematic indicators (e.g. asymmetry of S-shaped microfabrics) recorded by the fabrics (Figs. 2 and 4 to 11) are consistent throughout the tills and record a north-directed sense of shear, coincident with the regional ice flow pattern across this part of NE Scotland (see Fig. 3).

Microstructures formed in response to the rotation of granule and pebble-sized clasts (arcuate grain alignments, small-scale crenulations) during deformation are preserved within the matrix immediately adjacent to these larger clasts, as well as within the microlithons separating the S1 and S2 microfabrics (Figs. 2, 4 and 5). Rotational structures, including turbate structures (van der Meer, 1993, 1997; Menzies, 2000; Hiemstra and Rijsdijk, 2003), are truncated by the clast microfabrics, indicating that they formed prior to, or during the early stages of foliation development. Comparable rotational structures have also been identified in mass flow deposits were they have been interpreted as forming in response to turbulent flow during emplacement (Lachniet *et al*., 2001; Phillips, 2006). Turbate structures form where clasts rotate through angles of up to, and greater than 360°, entraining the adjacent finer-grained matrix (van der Meer, 1993; Menzies, 2000). This requires either very high shear strains or the lowering of the shear strength of the till due to liquefaction, allowing the rotation of the clasts at much lower strains (Evans *et al*., 2006).

In samples N7126 and N7128 the style and relative intensity of the fabrics is highly variable (Figs. 2, 6 and 7). In the more matrix-rich areas, although both S2 and S3 are present, the earlier S1 fabric is relatively weak or absent. In sample N7128 (Fig. 7), S1 is most pronounced within the upper part of the thin section where it is deformed by an open fold and its associated up-ice dipping axial planar S2 fabric. In the slightly sandier core of this fold, however, S1 is apparently absent. The finer grained areas are interpreted as veins and patches of liquefied sediment injected into the till during deformation, between the imposition of S1 and the later S2 and S3 foliations (Phillips *et al*., 2011). Variation in the overburden pressure exerted in the TMZ by the overlying ice may have resulted in the collapse of the till and "squeezing out" of the liquefied sediment which is then injected into lower strain areas to form cross-cutting veinlets and/or patches of massive till. Deformation of the relatively weak till within the TMZ appears to have been associated with expansion (volume increase) and resulted in localised folding of S1. Subsequent shearing within the TMZ would then lead to renewed foliation development and deformation of the recently injected veins (see Fig. 2). Engineering studies have shown that the inherent density contrasts between an injected fluid and the host material will result in the escaping water-sediment mix being driven upwards towards the surface (Abou-Sayed *et al*., 1984). In the subglacial environment this means that the liquefied till will be preferentially injected upwards towards the top of the TMZ and the ice-bed interface (Fig. 2; also see Fig. 14), as long as water pressures at the ice-bed interface are not elevated due to strong surface melting.

Although the majority of the tills from the Nairn area, like many other subglacial traction tills, appear massive in the field, a subhorizontal stratification is locally apparent in thin section where it is defined by laterally impersistent, wispy-looking lenses composed of slightly darker, more matrix-rich diamicton (N12280, N12281; Figs. 2, 8 and 9). The margins of these lenses are highly irregular to flame-like in nature and are gradational over several millimetres (Fig. 8), resulting in a distinctive "diffuse" to "mottled" appearance to the diamicton. Samples N12280 and N12281 were collected from the same till unit (N12281 collected 50 cm above N12280) and demonstrate that the stratification is variably developed/preserved. The shear related microfabrics clearly cross-cut the layering (Figs. 2, 8 and 9) indicating that their imposition post-dated this stratification.

The simplest interpretation of the highly complex stratification present within these two thin sections is that they record the progressive overprinting of the primary layering (e.g. bedding) within this till (Fig 2). Rather than being a product of deformation, the complexity of this stratification is indicative of the disruption typically associated with liquefaction (Phillips *et al*., 2007; Phillips *et al*., 2013b). Localised saturation of the till may have occurred in response to either the migration of porewater through the sediment and/or the introduction of pressurised meltwater into the bed from the overlying ice. The migration and/or introduction of pressurised meltwater into the bed is supported by a number of studies on modern glaciers (Hooke, 1984; Engelhardt and Kamb, 1997; Hooke *et al*., 1997; Bartholomaus *et al*., 2008; Schoof *et al*., 2014; Andrews *et al*., 2014) which have shown that subglacial water pressures are extremely variable over space and time. Loading (compression) or shear (simple shear) of these water-saturated sediments will lead to an increase in intergranular PWP, lowering of the shear strength of the till, and ultimately a loss in the integrity of the sediment. The increase in intergranular PWP forced the constituent grains apart, leading to a reduction in intergranular contacts, lowering the density of the packing of the constituent sand grains, and increasing the volume of the sediment, which ultimately led to localised liquefaction. The increase in the connectivity of the intergranular pore spaces during this process would result in an increase in permeability, enabling the porewater to move/disperse through the sediment and drain away from the liquefied till, leading to "collapse" and solidification the sediment. Repeated phases of liquefaction, potentially coupled with the mobilisation/displacement of the liquefied sediment, would result in a loss of integrity of the original compositional layering, leading to mixing and eventual homogenisation of the till. The shear related microfabrics clearly cross-cut the layering (Figs. 2, 8 and 9), indicating that their imposition post-dated liquefaction and the disruption of this stratification.

Two samples of till from the Nairn area (N12278, Fig. 10 and N1279, Fig. 11) are cut by irregular, down-ice dipping veins of silty sand (Fig. 2). The sand is lithologically similar (contains the same range of clast types) to the matrix of the host diamicton indicating that they were derived from the same source. Rather than being sharp planar features, the vein margins are highly complex to gradational, suggesting that they were introduced into the till whilst it was still relatively weak (water-rich/saturated). The veins are coplanar to S3 (Fig. 11) and the down-ice dipping Riedel shears (R-type shears; see inset Fig. 2). Extension occurring across these narrow ductile shear zones aided hydrofracture propagation and the simultaneous injection of the liquefied sand (c.f. cut-and-fill of hydrofractures proposed by Larsen and Mangerud, 1992), indicating that liquefaction was also occurring during the imposition of S3 and the final stages of subglacial deformation. Shear induced by the injection of the pressurised liquefied sediment may have resulted in the observed complex, soft-sediment deformation along the walls of the vein.

Further evidence for the liquefaction, mobilisation and injection of till within the subglacial environment is provided by a detailed microstructural and sedimentological study of thinly stratified tills exposed at Galmis, Switzerland (van der Meer, 1979; 1982; Phillips *et al*., 2013b). Phillips *et al*. (2013b) interpreted the micromorphology of the Galmis till as recording a complex history of deformation, liquefaction and sedimentation during repeated phases of basal sliding as the ice overrode a soft-sediment bed (Fig. 12). The till comprises alternating layers of massive to weakly foliated diamicton and variably deformed laminated silt and clay. It is argued that elevated porewater contents encountered immediately prior to, and during, basal sliding promoted localised liquefaction of the underlying diamicton, with the decoupling of the glacier from its bed enabling the injection of this liquefied sediment along the ice-bed interface and/or into the laminated sediments. Phillips *et al*. (2013b) concluded that the laminated sediments record the settling out of fines (clay, silt) from meltwater trapped along the ice-bed interface after an individual phase of basal sliding has ceased. Injection of the pressurised till into the locally water-saturated silts and clays resulted in partial liquefaction and incomplete mixing ('vinaigrette-like' texture) of these fine-grained sediments with the diamicton (Fig. 12). Recoupling of the ice with its bed led to bed deformation and localised folding and thrusting of the laminated sediments, as well as incipient microfabric development within the diamicton layers. Initial estimates of the strains imposed on these stratified tills indicates that the amount of shear transmitted into the soft-sediment bed during basal sliding are relatively low, allowing the preservation of the fine-scale stratification within the Galmis tills.

3. Soft bed deformation/sliding and the potential for till liquefaction

The concept of subglacial till-forming mosaics, in which the processes of deformation and soft bed sliding/ploughing operate as a spatial and temporal continuum, has been widely promoted (e.g. Piotrowski and Kraus, 1997; Boyce and Eyles, 2000; van der Meer et al., 2003; Larsen *et al*., 2004, 2007; Piotrowski *et al*., 2004, 2006; Evans *et al*., 2006; Lee and Phillips, 2008; Meriano and Eyles, 2009) and is encapsulated herein by our transient mobile zone (TMZ). This recognition of the spatial and temporal variations in subglacial deforming bed processes also acknowledges that changing water pressures, even at diurnal temporal scales, may result in cycles of decoupling and coupling of the glacier from its bed (e.g. Boulton and Dobbie, 1998; Boulton *et al*., 2001) and the operation of stick-slip ice motion (e.g. Fischer and Clarke, 1997). The spatial variability in sliding versus deformation also gives rise to the development of 'sticky spots' on the glacier bed (Alley, 1993; Stokes *et al*., 2007).

The stick-slip cycle of sliding and deformation proposed by Boulton *et al*. (2001) accounts for the soft-bed sliding (ploughing) process (Brown *et al*., 1987; Tulaczyk *et al*., 2001; Clark *et al*., 2003), when shear stress and water pressure build to the point where till dilates, ice-bed friction is reduced and ice-till decoupling takes place. When water pressures in the dilatant till fall, deformation and ice-bed coupling take over and there is a reduction in the amount of sliding. A continued fall in water pressures then consolidates the dilatant till, enhancing the transmission of strain through this sediment and deeper into the bed, thereby causing the shear zone to migrate downwards through the till. Deformation may stop once the water pressure falls below the critical level for failure, forming a sticky spot. The diurnal changes in water pressure are thought to lead to repeat cycles of dilation and collapse so that the classic curvilinear till displacement curve, which represents cumulative strain, becomes more pronounced with time.

Given the important role of variable porewater pressure cycles in driving the stick-slip motion observed at modern glacier beds, the evidence for potential multiple liquefaction events in the subglacial traction tills reported in the Scotland and Switzerland case studies is highly-significant with respect to the exact modes of operation of the subglacial deforming layer and till production. The micromorphological evidence for repeated phases of liquefaction followed by solid-state shear deformation, indicates that the operation of the TMZ involves slip events driven by not only the already widely acknowledged processes of pressurised meltwater and porewater but also the episodic liquefaction of water-saturated till.

4. Potential controls on liquefaction and soft-bed deformation/sliding

As identified above, rather than being a continuous uninterrupted cyclical process, the generally accepted view of the forward motion of a glacier is in terms of a series of 'stick-slip' events (Fischer and Clarke, 1997; Fischer *et al*., 1999; Wiens *et al*., 2008). One major controlling factor responsible for the glacier 'sticking' to its bed is the downward force imposed by the overlying ice. This overburden pressure results in an increase in the packing of the sediments (consolidation), increasing their shear strength, which in turn restricts forward motion of the glacier as a result of soft-bed sliding. The individual slip events will likely be relatively short-lived, but over time allow the glacier to move forward without becoming unstable. Importantly the slip events occur repeatedly throughout both the summer and winter months requiring that any potential control on soft-bed sliding needs to operate throughout the year. Three potential controls on soft-bed sliding appear to be operating in glacial systems, one of which we hypothesize to be the now widely recognized phenomenon of glacier-related seismicity.

4.1. Control 1: pressurised meltwater

The most commonly cited control on enhanced bed deformation is the introduction of pressurised meltwater into the subglacial environment (e.g. Bartholomaus *et al*., 2008). This hypothesis is supported by a number of studies of modern glacier systems which have clearly demonstrated that higher meltwater production during the spring and summer months coincide with an increase in ice surface velocity (Iken *et al*., 1983; Iken and Bindschadler, 1986; Nienow *et al*., 2005). This spring-summer 'speed-up' is subsequently followed by a decrease in velocity during the autumn and winter as meltwater production declines and the subglacial hydrogeological system in many glaciers begins to shut down. It is possible that the decrease in surface velocity towards the end of the spring-summer 'speed-up' is also governed by the increased maturation of the subglacial drainage system (e.g. Werder *et al*., 2013) and the formation of channels which help drain the bed. The porosity and permeability of subglacial sediments will directly affect the rate at which meltwater can penetrate into and migrate through the bed. Several micromorphology studies (Kilfeather and van der Meer, 2006; Tarplee *et al*., 2010) have demonstrated that porosity in tills plays a much more important role in bed deformation than previously thought, confirming the relationship between porosity and bed deformation proposed by Tulaczyk *et al*., (2000b) in his undrained plastic bed model.

Although clay-rich sediments possess a high intergranular porosity, they typically act as an aquitard forming an impermeable barrier at the base of the glacier, leading to the concentration of meltwater and therefore displacement at, or close to, the ice-bed interface (Boulton, 1996a, b; Engelhardt and Kamb, 1998; Tulaczyk, 1999). For example, at one location at the base of Ice Stream B (Whillans Ice Stream), Engelhardt and Kamb (1998) demonstrated that glacier flow was controlled by sliding over a clay-rich till. The clay-rich nature of the till retards water migration allowing the build-up of high porewater pressures and leading to glacier decoupling and thereby promoting forward motion due to basal sliding. This periodic decoupling of the glacier from its bed due to increased basal water pressures prevents the transmission of stress to the substrate (cf. Fischer and Clarke, 1997; Winberry *et al*., 2009; Iverson, 2010) effectively switching off bed deformation and/or soft-bed sliding, and promoting basal sliding. This has been proposed in order to explain the apparent lack of pervasive subglacial deformation structures within a number of till sequences found in the geological record (Brown *et al*., 1987; Clark and Hansel, 1989; Piotrowski and Kraus, 1997; Piotrowski and Tulaczyk, 1999; Piotrowski *et al*., 1999, 2001, 2002; Hoffmann and Piotrowski, 2001; Lee and Phillips, 2008; Phillips *et al*., 2013b; Lee *et al*., 2016).

In contrast to clay-rich subglacial sediments, highly-permeable sands and gravels provide an ideal fluid pathway which can promote dewatering of the bed, effectively switching off soft-bed sliding and basal-slip. This illustrates the potential lithological control on not only the subglacial hydrological system but also the mechanism for glacier motion across its bed. In a theoretical overview of the deformation process, Boulton (1996) suggested that clay-rich tills do not couple to the ice base as well as coarse-grained tills and will only deform to a shallow depth. This implies that the relative importance of sliding versus deformation will vary according to the granulometry of the glacier bed. Consequently, it is possible that the presence of coarse-grained, permeable sediments beneath glaciers could represent a major factor governing the formation of “sticky spots” beneath the overriding ice. However, a study by Salamon (2016) on the subglacial conditions beneath the Weichselian Scandinavian ice sheet in southern Poland suggests that despite the high permeability of the coarse-grained sediments within its bed, ice sheet movement was not impeded. In this case forward motion is believed to have been accomplished by a combination of basal slip and localised shallow bed deformation due to high basal water pressures resulting from permafrost restricting subglacial groundwater outflow. Consequently the potential for soft-bed sliding to be initiated is not only dependent on the permeability of the substratum, but also the connectivity of the aquifer and the presence of hydraulic pathways which facilitate/promote the dewatering of the bed.

One potential way to promote soft-bed sliding would be to increase the volume of meltwater reaching the bed. However, where the bed is composed of low to moderately permeable sediments this is more likely to overwhelm the rate at which these sediments can transmit large volumes of fluid. The direct result would be the development of a stable (channelized) subglacial drainage system. This highly efficient drainage system would rapidly remove any excess meltwater from the subglacial environment, leading to the dewatering of the bed. Furthermore several studies suggest that during periods of low flow, the lowering of the water levels within subglacial drainage channels leads to the development of a hydrostatic gradient towards these open conduits, promoting the dewatering of the sediments adjacent to the channel walls (Hubbard *et al*., 1995; Boulton *et al*., 2007a, b; Magnússon *et al*., 2010).

An alternative approach to increasing the volume of meltwater reaching the base of glacier is to increase the pressure of the subglacial meltwater system. An increase in the effective pressure (ice overburden minus water pressure) would help drive water from the ice-bed interface into the bed, overcoming the limiting factor presented by the permeability of the till. However, if the pressure exceeds the shear strength of the sediment it will result in hydrofracturing of either the bed and/or overlying ice. Hydrofracture systems are increasingly being recognised in glacial environments and provide clear evidence for the movement of pressurised meltwater through subglacial to ice-marginal settings (Dionne and Shilts, 1974; Christiansen *et al*., 1982; von Brunn and Talbot, 1986; Burbridge *et al*., 1988; Dreimanis, 1992; Larsen and Mangerud, 1992; McCabe and Dardis, 1994; Dreimanis and Rappol, 1997; van der Meer *et al*., 1999; Rijsdijk *et al*., 1999; Le Heron and Etienne, 2005; Boulton, 2006; Goździk and van Loon, 2007; van der Meer *et al*., 2009; Phillips and Merritt, 2008; Phillips *et al*., 2013a; Phillips and Hughes, 2014). They record marked changes in hydrostatic pressure within the subglacial meltwater system, leading to brittle fracturing and penecontemporaneous liquefaction and the introduction of a sediment-fill, and can occur in both soft (sedimentary) and/or hard (bedrock) beds (see van der Meer *et al*., 2009; Phillips *et al*., 2013a). Due to the pressurised nature of the meltwater, the sediment-fill can be introduced from structurally above (downward injection) or below (upward injection) the developing hydrofracture system (Dreimanis, 1992; Rijsdijk *et al.,* 1999; Le Heron and Etienne, 2005; Goździk and van Loon, 2007; van der Meer *et al*., 2009). Furthermore, it is becoming increasingly apparent that the introduction of pressurised meltwater can have a profound effect on subglacial to ice-marginal deformation. It can, for example, aid the development of water-lubricated detachments within the sediment pile (e.g. Phillips *et al*., 2002; Benediktsson *et al*., 2008; Vaughan-Hirsch and Phillips, 2016) and thereby promote rapid ice movement (e.g. Kjær *et al*., 2006), and aid the initial detachment and transport of sediment and/or bedrock rafts (e.g. Moran *et al*., 1980; Broster and Seaman, 1991; Phillips and Merritt, 2008; Burke *et al*., 2009; Vaughan-Hirsh *et al*., 2013). Several studies have shown that once formed, hydrofracture systems can be reactivated on multiple occasions (Phillips and Merritt, 2008; Phillips *et al*., 2013a; Phillips and Hughes, 2014; Lee *et al*., 2015) and as a result have the potential to profoundly influence subglacial drainage. The overpressurised states required to reactivate an existing hydrofracture system are likely to be much lower than those required during its initial formation, in effect forming the "pressure release valve" proposed by van der Meer *et al*. (2009). Consequently, the introduction of pressurised meltwater into the sediments beneath the ice as a trigger for bed deformation and/or soft-bed sliding will be controlled by their permeability and shear strength. Both of these factors will have a direct impact on the magnitude of the fluid pressures which can be achieved before the onset of hydrofracturing, leading to draining of the bed and depressurisation of the system.

4.2. Control 2: glacitectonism

A second potential control on increasing the intergranular porewater pressure leading to liquefaction in subglacial sediments is glacitectonism. Compression resulting from folding and/or the stacking/imbrication of fault-bound slabs of sediment during thrusting can lead to a localised increase in overburden pressure. This in-turn can lead to an increase in porewater pressure and potential liquefaction in response to the glacitectonic thickening of the bed. However, the thrust planes or ductile shear zones responsible for this imbrication have the potential to act as fluid pathways, helping to transmit water through the deforming sediment pile (Benediktsson *et al*., 2008; Lee and Phillips, 2008; Phillips *et al*., 2008; Vaughan-Hirsch and Phillips, 2016). Migration of meltwater along these potentially laterally extensive glacitectonic structures is driven by the hydropotential gradient, resulting from the increased overburden pressure and/or compression deeper within the deforming sequence. This could lead to the dewatering of the sediment and transition from initial ductile shearing to subsequent brittle deformation.

Importantly, thrusting and stacking of detached slabs of till is only likely to occur at the glacier margin where the ice is thinnest (Evans and Hiemstra, 2005; Hiemstra *et al*., 2007; Lee *et al*., 2016; Vaughan-Hirsch and Phillips, 2016). Further up-ice, large-scale tectonic thickening of the bed is less likely as not only is this an area of low driving stress but also the process requires the glacier to be lifted vertically to overcome the relatively high overburden pressures and to provide the required accommodation space for the stacking (imbrication) of the detached thrust slices. Consequently, the thickening of the bed in response to large-scale glacitectonic thrusting is less likely to be a contributing factor to triggering liquefaction and soft-bed sliding.

4.3. Control 3: glacier related seismicity

A third and potentially more important control on liquefaction, and thereby soft-bed sliding, which has yet to be considered by the glaciological community is the seismicity caused by icequakes or glacier quakes. Recent studies in modern glacial environments (e.g. Ekstrom *et al*., 2003; Ekstrom *et al*., 2006; Tsai and Ekstrom, 2007; Wiens *et al*., 2008; Peng *et al*., 2014; Lipovsky and Dunham, 2016; Podolskiy *et al*., 2016) have demonstrated that modern glaciers are seismically active with icequakes occurring in response to movement on faults within the glacier or underlying bed, crevasse/fracture propagation, iceberg calving, seracs toppling in ice-falls, opening and closing of englacial drainage conduits and/or slip events at the ice base. These processes are an integral part of glacier flow and as such can occur along the entire length of the glacier and also throughout the year. Seismic events related to these processes are therefore continually releasing energy into the surrounding ice and underlying bed. Wiens *et al*., (2008) have shown that these events can release over a prolonged period of time (e.g. up to 30 minutes) the same amount of energy as a moment magnitude 7 earthquake. However, the seismic amplitudes are modest (Ms 3.6–4.2) due to the long source duration of these events (Wiens *et al*., 2008). The energy released from an ice-quake can also travel in all directions, and therefore migrate both up- and down-ice from its hypocentre (focus). Consequently the seismic effects of, for example, a large iceberg calving event at the glacier margin has the potential to have an impact several kilometres up-ice. Seismic signals can also be generated by slip initiation at the glacier bed (Wiens *et al*., 2008; Walter *et al*., 2011; Lipovsky and Dunham, 2016).

The liquefaction of unconsolidated sediments as a result of the seismicity caused by earthquakes is well-known and represents a major geological hazard (Holzer *et al*., 1989; Youd, 2003; Miwa *et al*., 2006). Evidence of palaeoseismic induced liquefaction (seismites) has also been reported from the geological record (Obermeier, 1998; Menzies and Taylor, 2003; Green *et al*., 2005; Obermeier *et al*., 2005). Seismically induced liquefaction depends upon several factors, including earthquake moment magnitude (i.e. total energy released), shaking duration, peak ground motion, depth to groundwater table, susceptibility of sediments to liquefaction, and water saturation (Youd, 1978; Youd, 2003 and references therein). Liquefaction is typically observed associated with earthquakes of magnitude 5 or above. However, it can also occur in water-saturated sediments at much lower magnitudes, for example during the 1865 Barrow (UK) earthquake, a very shallow focus low moment magnitude (Mw 3) quake generated localised liquefaction and formation of sand volcanoes in the saturated tidal sands of Morecambe Bay (R. Musson pers. comm.). Importantly, this instability may remain after the initial event which triggered liquefaction has passed/dissipated with subsequent, smaller aftershocks potentially leading to further/renewed liquefaction of the superficial deposits even at lower magnitudes.

A direct link between glacier seismicity and the localised liquefaction of the soft, unconsolidated sediments within the bed has yet to be demonstrated in contemporary glacial environments. However, the magnitude and duration of icequakes reported in the literature (e.g. Ekstrom *et al*., 2003) do compare favourably with earthquakes which are known to have induced liquefaction. Furthermore, the sediments forming the bed of a glacier meet the criteria required for seismically induced liquefaction, in particular: they are typically composed of unconsolidated, granular sediments which have the potential to undergo liquefaction; they can possess a high water content and are at, or near saturation; and the water table within subglacial environments is high or even perched, being constrained within the soft bed by the underlying less permeable bedrock and the overlying ice. Consequently, it is feasible that the energy released during the larger icequakes has the potential to result in liquefaction and sliding within the underlying soft-sediment bed. It is important to stress that seismically induced liquefaction of the bed would be localised in nature as a direct consequence of the spatial and temporal variation in sediment grain size, composition, porosity, permeability and water content. Furthermore, the consolidation of subglacial sediments is very variable. Subglacial sediments are typically consolidated, with lower consolidation ratios in actively deforming “slippery spots” within the bed (Clarke, 1987; Boulton and Dobbie, 1993; Tulaczyk *et al*., 2000; Leeman *et al*., 2016). Basal freeze-on can also further elevate consolidation ratios by removing water from the till (Christoffersen and Tulaczyk, 2003a, b) further adding to the localised nature of the potential for soft-bed sliding. The confining pressure exerted by the ice can also prevent dilation and/or liquefaction of the sediments within the bed, effectively applying a ‘breaking mechanism’ to glacier motion. Consequently, liquefaction and soft-bed sliding is likely to only occur in response to icequakes over a certain magnitude, once again promoting a "stick-slip" style of glacier motion.

5. Seismically induced soft-bed sliding in subglacial sediments?

During an icequake the pulse of energy released passes through the ice and into the underlying water saturated sediments and has the potential to provide a 'trigger' for dilation and transient liquefaction, and soft-bed sliding (Figs. 13 and 14). On a granular scale this relatively short duration pulse of energy causes the individual clasts within the sediment to vibrate, modifying the packing of the grains and leading to the pressurisation of the intergranular porewater (Fig. 13). Seismicity will cause liquefaction if it results in the effective stress becoming zero or negative, so that porewater completely relieves the granular skeleton of its compressive stresses (Zhang and Campbell, 1992; Xu and Yu, 1997). The effect of this sudden increase in PWP is to reduce the number of grain to grain contacts, allowing the individual clasts to move (slide or rotate) past one another. The net effect is to reduce sediment shear strength, leading to dilation and thereby allowing soft-bed sliding to occur. This seismically induced 'vibrating' effect would propagate away from the focus of the ice-quake as a pulse or series of pulses (i.e. shear waves or 'S-waves'). Thus, if the porewater pressure anomaly is sufficiently large, areas of the subglacial bed would initially undergo localised soft-bed sliding, followed by stabilisation outwards away from the icequake focus as a result of dewatering. Youd (2003) describes how the oscillating ground motion caused during an earthquake results in repeated reversals in the direction of shear releasing the effects of dilative arrest and resulting in repeated episodes of liquefaction and flow deformation as well as the arrest process. If applicable to the subglacial environment, this cyclic liquefaction (Youd, 2003) would potentially aid in maintaining soft-bed sliding during the duration of the icequake (potentially up to several minutes). However, dilative arrest (Youd, 2003) will result in the collapse and increased packing of the sediment (compaction) in effect switching off soft-bed sliding.

Due to the highly-heterogeneous nature of the sediments beneath glaciers, liquefaction leading to soft-bed sliding will be localised in nature, probably occurring within discrete, laterally discontinuous patches or narrow zones in the order of only a few centimetres or even millimetres thick. As liquefaction operates only in materials already at very low values of effective stress, it is most likely to take place only in glacier sub-marginal settings and hence its process-form signatures are indicative of glacier sub-marginal tills. The accompanying dilation will lead to a temporary increase in the connectivity between intergranular pore spaces within the sediment and therefore the permeability of the bed, enabling the transmission of porewater through the till (Fig. 13). This in turn could facilitate the migration of flow deformation (soft-bed sliding) through the TMZ (Fig. 14). The amount of forward movement accommodated/achieved during an individual icequake induced 'slip event' is likely to be relatively small. However, this displacement may, in itself, trigger further smaller seismic events within the bed or at the ice-bed interface (see Fig. 14), and thereby help to maintain soft-bed sliding after the initial seismic trigger has passed. As soon as the energy released by the icequake has been dissipated (probably taking only a few minutes), the fall in intergranular PWP and increase in sediment shear strength will result in the cessation of flow deformation, and hence forward movement will stop.

Spatial variation in, for example, ice thickness will lead to the variation in the magnitude of the overburden pressure being exerted on the underlying bed. The resultant hydrostatic pressure gradients will facilitate or even promote the displacement (mobilisation) of the liquefied sediment and its injection into relatively lower pressure areas within the bed (Fig. 14). As a result, flow deformation and soft-bed sliding would migrate through the bed (labelled 1 to 4 on Fig. 14). The positive buoyancy of liquefied sediments means that migration will occur both laterally and vertically, with the fluidised sediment preferentially migrating upwards through the bed were it will be confined at, or close to the ice-bed interface (Fig. 14; also see Fig. 2). This may lead to the effective dewatering of the structurally lower parts of the bed and an increase in the height of the water table toward the base of the glacier. Over time the net result will be for forward motion of the glacier due to soft-bed sliding, preferentially concentrated within the upper part of the bed (Fig. 14). The presence of a less permeable or more cohesive (i.e. clay-rich) layer or even an overridden (buried) permafrost layer within the bed, however, may impair the upward migration of the liquefied sediment, trapping it at a lower structural level and leading to forward motion being accommodated at this deeper level (Fig. 14).

6. Feedback mechanism leading to glacier motion

In reality glacier movement due to soft-bed sliding will be controlled by subglacial PWP, glacier seismic activity and deformation (Fig. 15a). The interplay between these factors is thought to lead to a feedback mechanism which helps maintain glacier motion (Fig. 15b). The cycle begins with an icequake associated with ice deformation, potentially leading to localised liquefaction of the underlying sediments, triggering soft-bed sliding within the bed. This forward movement leads to further extensional deformation (crevassing) within the ice and continued seismic activity, which in turn triggers further sliding and the cycle starts again (Fig. 15b). Importantly, ice deformation and the associated seismicity is a relatively continuous process that occurs throughout the year, enabling forward motion of the glacier to be maintained. In addition, seasonal increases in meltwater productivity can potentially facilitate movement by increasing the saturation of the bed, leading to either increasing amounts of soft-bed sliding and/or basal sliding. However, dewatering of the bed, either due to the development of a stable subglacial drainage system and/or hydrofracturing, will disrupt this feedback loop and “switch off” forward movement.

Fast flowing glaciers and ice streams are characteristically highly crevassed (see Benn and Evans, 2010 and references therein) and are therefore likely to be more seismically active, leading to an increase in the rate at which they pass through the feedback loop (Fig. 15b). Large-scale (decadal) fluctuations in subglacial hydrogeology (Clarke, 2005) may promote a periodicity within this feedback mechanism potentially leading to surge-type behaviour. Alternatively, if conditions conducive to soft-bed sliding and basal sliding are maintained then the repeated “cycling” of the feedback loop has the potential to result in fast ice flow and ice streaming. Tidal modulation of subglacial stresses and stick-slip motion has also been proposed for tidewater or floating glacier snouts by Bindschadler *et al*. (2003a, b) and Walker *et al*. (2013). Such external controls on stick-slip motion, and indeed on icequake activity, are likely to play a more dominant role than those operating under thicker ice, where basal driving stress predominantly exceeds sediment strength so that deformation is a continuous uninterrupted process (e.g. Schofield and Wroth, 1968; Iverson *et al*., 1998; Tulaczyk *et al*., 2000a; Damsgaard *et al*., 2013, 2015). In contrast, the sticky spots identified on ice stream beds represent the very few places where till strength is sufficiently high enough to exceed driving stress (e.g. Alley, 1993; Joughin *et al*., 2004) and hence arrest deformation. The higher effective pressures beneath such areas of thicker ice make it unlikely that liquefaction could operate in the subglacial deforming till mosaic. But the existence of materials already at low values of effective stress for at least part of the time in glacier sub-marginal settings make this a prime location for the operation of liquefaction in response to glacier seismicity (cf. Zhang and Campbell, 1992; Xu and Yu, 1997) and hence its process-form signatures are likely indicative of glacier sub-marginal tills.

7. Conclusions

This paper provides a review of the theoretical models of glacier forward motion involving deformation of the soft-sediments within the underlying bed. The results of several detailed microstructural studies clearly demonstrate that this deformation results in the development of a range of ductile and brittle structures as these potentially water-saturated sediments accommodate the shearing being applied by the overriding glacier. The geometry of the clast microfabrics developed within matrix of these polydeformed subglacial traction tills are consistent with the development of Riedel shears within a subhorizontal or very gently dipping shear zone located within the bed of the overriding ice. Furthermore, these studies also reveal that tills may also contain evidence of having undergone repeated phases of liquefaction prior to a final phase of solid-state shear deformation as this subglacial shear zone begins to lock up. Liquefaction within the bed is short-lived and results in the lowering of the shear strength of the till. This leads to the formation of spatially and temporally restricted “transient mobile zones” within subglacial traction tills, effectively resulting in decoupling within the glacier bed, likely concentrated in glacier sub-marginal zones where materials are at low values of effective stress. This process is referred to as “soft-bed sliding” and forms part of a continuum with bed deformation and basal sliding that facilitate glacier movement. The spatial and temporal variations in the physical properties of subglacial traction tills means that the dominant mechanism responsible for their forward motion will also vary across the bed (spatial) and will change over time (temporal). Rather than being a continuous uninterrupted process, the generally accepted view is that glacier motion occurs in a series of ‘stick-slip’ events. Consequently it is essential for there to be a specific control built into the glacier system which enables forward motion to take place. The individual slip events resulting from liquefaction and soft-bed sliding are relatively short-lived, but over time allow the glacier to move forward without becoming unstable. Three potential controls are proposed: (i) the introduction of pressurised meltwater into the bed; (ii) the pressurisation of pore water already present within the till as a result of subglacial deformation; and (iii) the periodic liquefaction of water-saturated subglacial traction tills in response to glacier seismic activity (icequakes). In reality soft-bed sliding is likely to result as a consequence of the interplay between deformation, meltwater content/pressure and glacier seismic activity, and leading to a cyclic feedback mechanism that promotes the continued forward motion of the overriding ice mass.

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Figures

Fig. 1. Diagram showing the zonation of a relatively homogeneous subglacially deforming till and its relationship to “dilation”, displacement, sediment volume, shear strength, connectivity and pore water pressure (after Evans *et al*., 2006).

Fig. 2. Diagram showing the compiled results of a detailed micromorphological and microstructural study carried out on a series of subglacial traction tills exposed in the Nairn-Inverness area of NE Scotland (see text for details).

Fig. 3. Map showing the location of the Meads of St. John, Riereach Burn, Drynachan Burn, Dalcharn Burn, Cothall, Easterton farm and ‘stream’ sites in the Nairn-Inverness area of NE Scotland. Also shown are the generalized ice-movement directions within the Moray Firth Ice Stream and ice flowing northwards from the Cairngorm plateau across Lochindorb and down the valley of the River Findhorn.

Fig. 4. Microstructural map of a polydeformed subglacial traction till (sample N7126), the sandstone-rich Dalcharn Lower Till exposed in a river section at Dalcharn West [NH 8144 4528], NE Scotland (after Phillips *et al*., 2011).

Fig. 5. Microstructural map of a polydeformed subglacial traction till (sample N7128), the basal grey-brown metasandstone and granite-rich till exposed at Riereach Burn [NH 83903 43151], NE Scotland (after Phillips *et al*., 2011).

Fig. 6. Microstructural map of a polydeformed subglacial traction till (sample N7129), the basal grey-brown metasandstone and granite-rich till exposed at Riereach Burn [NH 83903 43151], NE Scotland (after Phillips *et al*., 2011).

Fig. 7. Microstructural map of a polydeformed subglacial traction till (sample N7132), the basal grey-brown metasandstone and granite-rich till exposed at Riereach Burn [NH 84503 44132], NE Scotland (after Phillips *et al*., 2011).

Fig. 8. Microstructural map of a polydeformed subglacial traction till (sample N12278) exposed at Cothall [NJ 04463 54103], NE Scotland.

Fig. 9. Microstructural map of a polydeformed subglacial traction till (sample N12279) exposed at Cothall [NJ 04463 54103], NE Scotland.

Fig. 10. Microstructural map of a polydeformed subglacial traction till (sample N12280) exposed at Nairn (stream) [NJ 04162 54102], NE Scotland.

Fig. 11. Microstructural map of a polydeformed subglacial traction till (sample N12281) exposed at Nairn (stream) [NJ 04162 54102], NE Scotland.

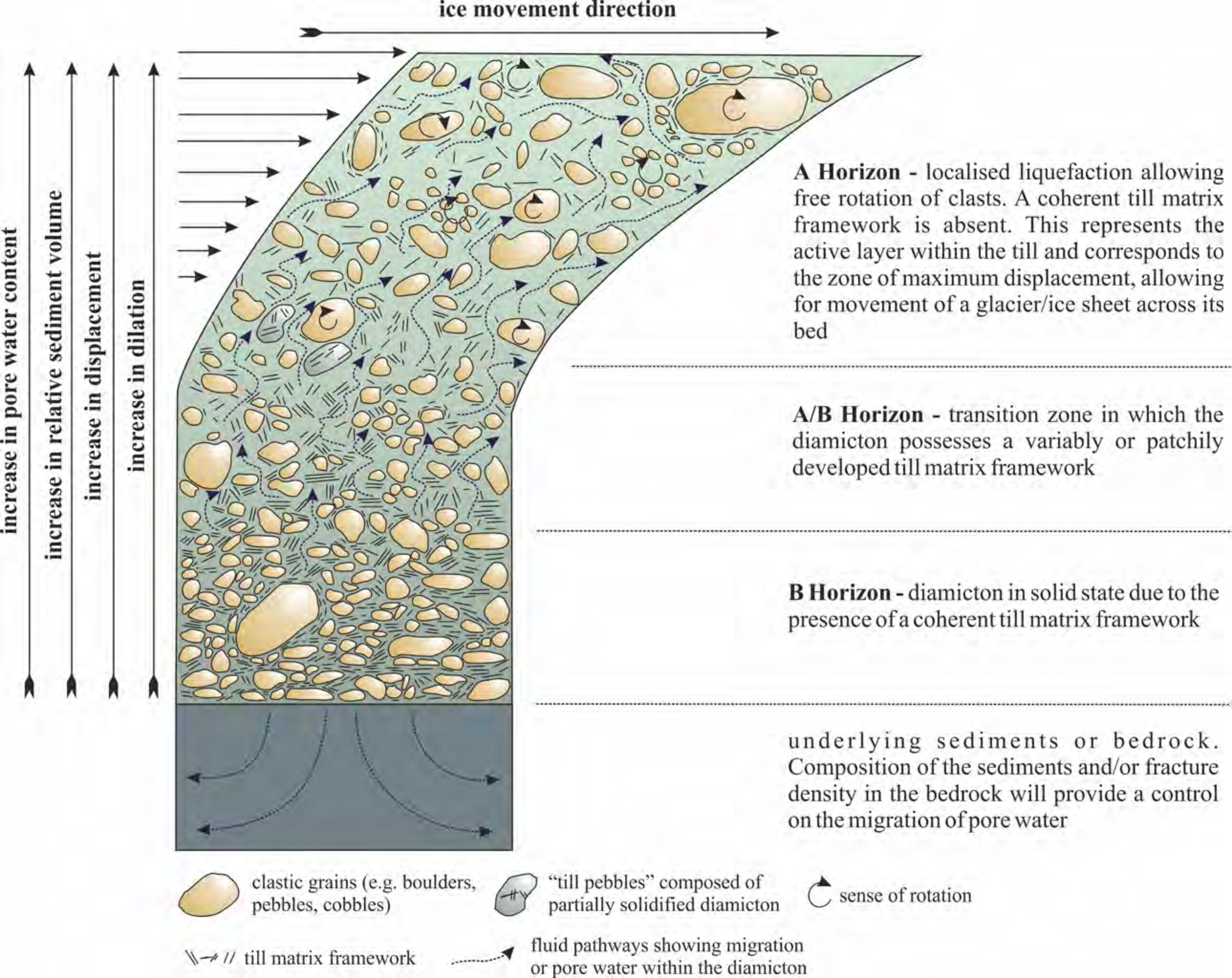
Fig. 12. Diagram showing the microstructural maps constructed for a series of thin sections taken from a thinly stratified till exposed at Galmis, Switzerland (Phillips *et al*., 2013).

Fig. 13. Diagram illustrating the effects of the seismic waves generated during an icequake on the unconsolidated sediments within the bed (see text for details).

Fig. 14. Diagram showing the proposed conceptual model leading to the development of a "transient mobile zone" (TMZ) within the bed of glacier in response to an icequake (see text for details).

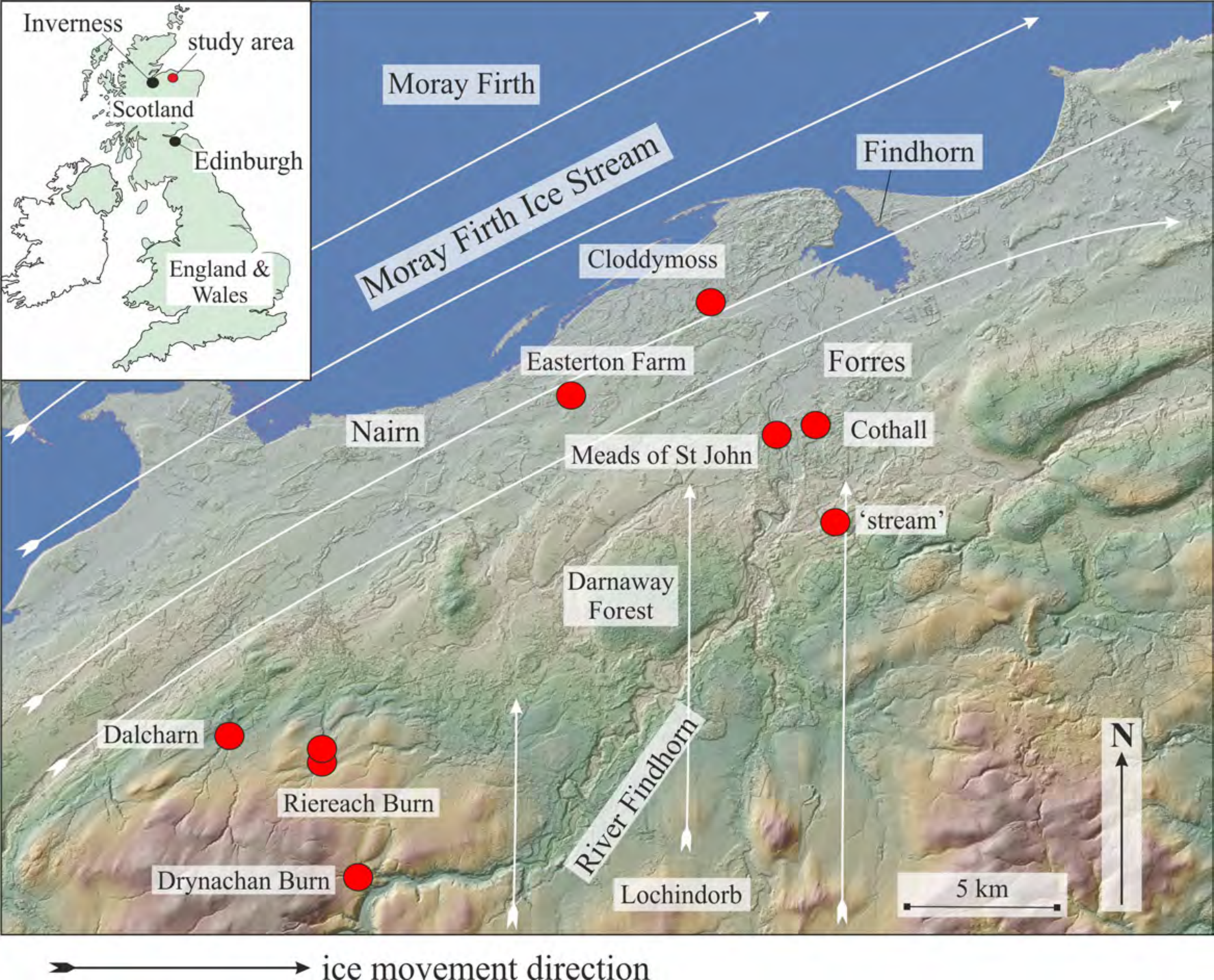
Fig. 15. (a) Schematic ternary diagram showing the relative effects of deformation, increased meltwater and ice quakes as potential triggers for soft-bed sliding versus bed deformation versus basal sliding as the main mechanism for glacier motion; and (b) Flow-chart showing the proposed

feedback mechanism responsible for promoting forward glacier motion as a result of soft-bed sliding induced by icequake activity.

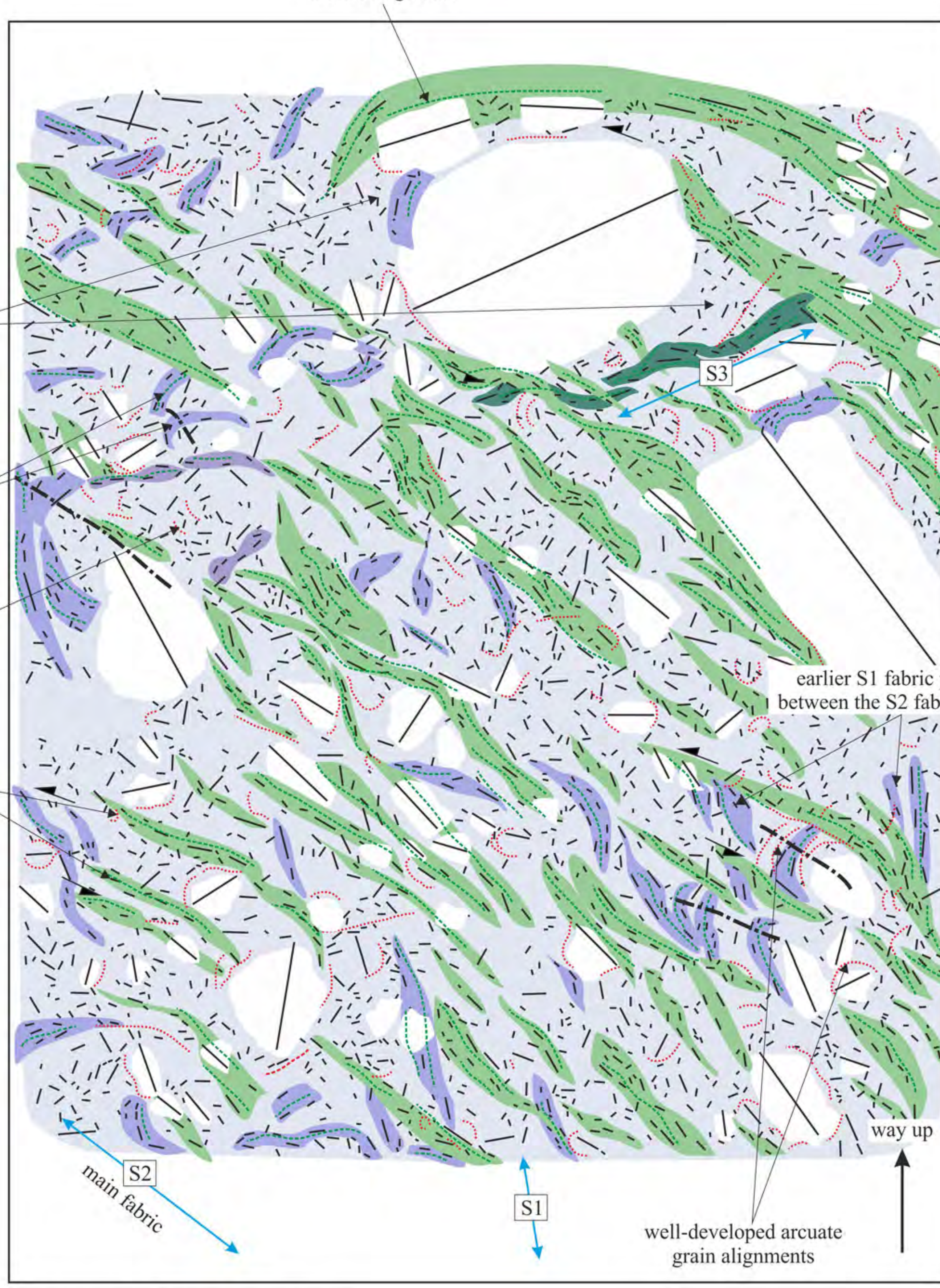


ice movement direction
increase in pore water content
increase in relative sediment volume
increase in displacement
increase in dilation
A Horizon - localised liquefaction allowing free rotation of clasts. A coherent till matrix framework is absent. This represents the active layer within the till and corresponds to the zone of maximum displacement, allowing for movement of a glacier/ice sheet across its bed
A/B Horizon - transition zone in which the diamicton possesses a variably or patchily developed till matrix framework
B Horizon - diamicton in solid state due to the presence of a coherent till matrix framework
underlying sediments or bedrock. Composition of the sediments and/or fracture density in the bedrock will provide a control on the migration of pore water
clastic grains (e.g. boulders, pebbles, cobbles)
"till pebbles" composed of partially solidified diamicton
sense of rotation
till matrix framework
fluid pathways showing migration or pore water within the diamicton

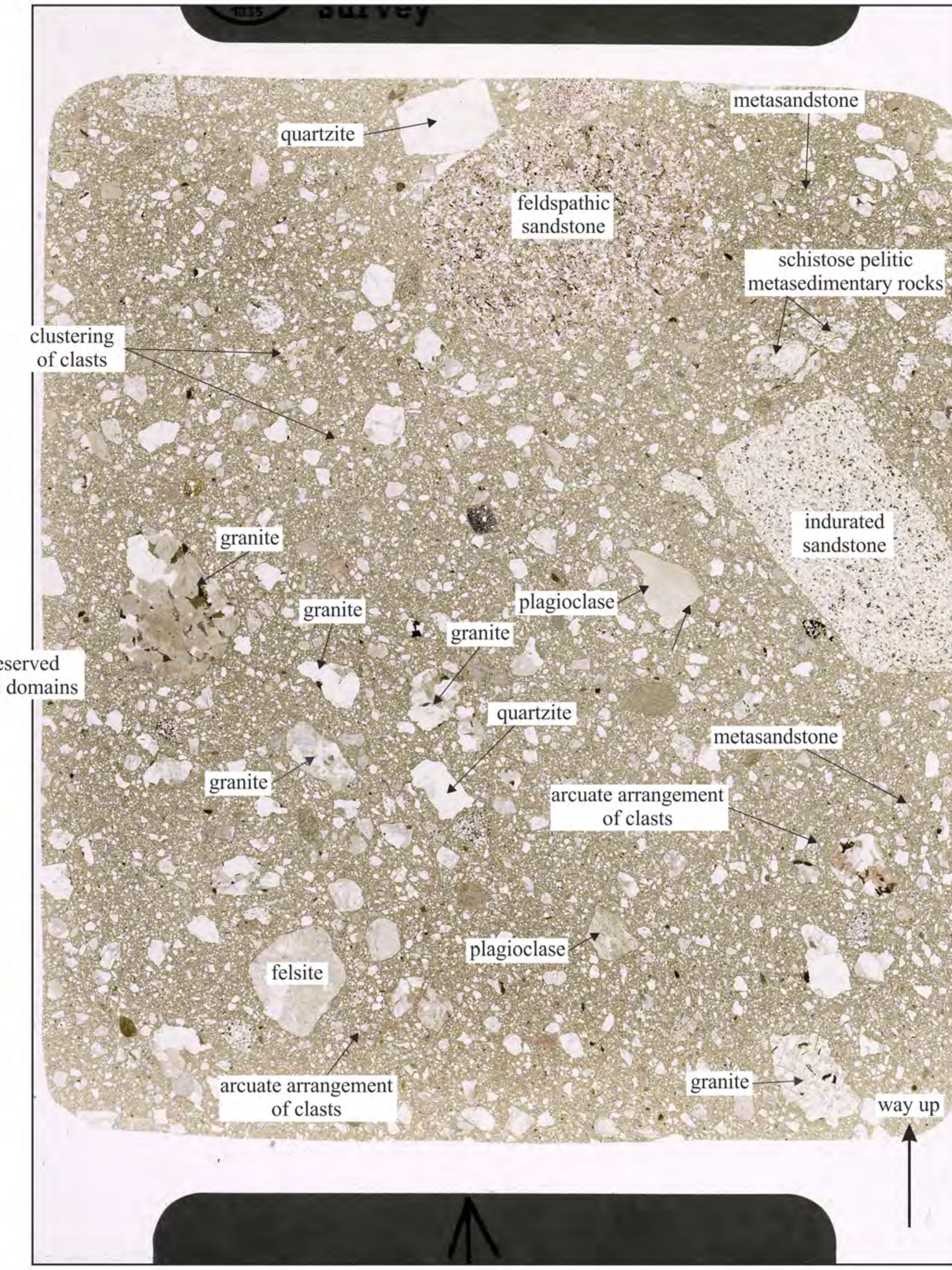
Glacier ice
movement direction of overriding glacier
"Mobile" layer within soft-sediment bed
Underlying diamicton
highly irregular, gradation/diffuse boundaries to stratification consistent with partial mixing of injected dilated/liquefied sediment with host diamicton
wipsy, diffuse layering or stratification
pressure shadows developed adjacent to larger clasts
folding of earlier fabric (S1) due to continued deformation
axial trace of fold
trace of open folds deforming earlier formed S1 clast microfabric
wrapping of fabric around larger clasts
S2 axial planar to folds deforming earlier S1 fabric
upward injection of liquefied sediment
S3 R Riedel shear
wrapping of S2 fabric around large clast
axial trace of fold
trace of open fold deforming earlier formed clast microfabric
S3 Riedel shear
S2 axial planar to folds deforming earlier S1 fabric
zone of 'intense' S2 fabric in hinge of fold
'expansion' due to injection of dilated/liquefied sediment
wrapping of S2 fabric around pebble in response to clast rotation
pressure shadows developed adjacent to larger clasts
S2 P Riedel shear
well-developed arcuate grain alignments
crenulation/microfolds deforming earlier developed S1 fabric
highly irregular, gradation/diffuse boundaries to veins
S3 Y Riedel shear
S3 R Riedel shear
irregular, diffuse veins of silty diamicton
sigmoidal fabric geometry to S3
way up
Sample N12280: Nairn (stream)
Sample N7126: Dalcharn 'Lower Till'
Sample N7128: Riereach Burn
Sample N7129: Riereach Burn
Sample N12278: Cothall
crenulations/microfolds deforming earlier fabric
well-developed arcuate grain alignments preserved in the microlithons of the S2 microfabric
S2 P Riedel shear
earlier S1 fabric preserved between the S2 fabric domains
tiling of clasts
arcuate grain alignments preferentially preserved between the S2 fabric domains
asymmetrical crenulation/microfolds developed adjacent to pebble due to localisation of shear along margin of this large clast
upward injection of dilated/liquefied sediment with host diamicton
highly irregular, gradation/diffuse boundaries to veins
irregular, diffuse veins of silt and silty diamicton
wipsy, diffuse layering or stratification
well-developed arcuate grain alignments
variably disrupted pre-existing stratification (bedding) within diamicton
S2 Riedel shear
Sample N12281: Nairn (stream)
Sample N7132: Riereach Burn
Sample N12279: Cothall
Top
sample N12279 all data (N = 2680)
inset: rose diagram showing and example of the clast long axis orientation data
inset: figure showing relationship between S1, S2 and S3, and Riedel shears formed in brittle and ductile shear zones
Y shear
R' shear
R shear
P shear
S
domains defining the S1 microfabric (oldest)
domains defining the S2 microfabric
domains defining the S3 microfabric (youngest)
preferred shape alignment of sand grains defining fabric
arcuate grain alignments and rotational structures
axes of folds and crenulations
sense of shear across Riedel shears
massive sandy matrix to diamicton
finer grained silt and silty sand matrix to diamicton
stratification in diamicton
sand and silty sand filling down-ice dipping veins
diffuse stratification in diamicton resulting from partial liquefaction and mixing of original layers within the till
highly irregular, complex/involuted boundaries between layers consistent with high pore water conents
clast microfabrics crosscut stratification in diamicton
arcuate grain alignments and rotational structures formed early associated with injection of liquified sediment and occur within microlithons of the early S1 clast microfabrics
cross-cutting veins/patches of diamicton recording multiple injection of liquefied sediment
wrapping of clast microfabrics around larger clasts due to simple shear and pure shear (loading) imposed by the overlying ice
typically down-ice dipping S1 fabric variably folded/crenulated and preserved in S2 microlithons
up-ice dipping S2 clast microfabric is the dominant foliation and occurs axial planar to, or slightly transgressing the folds deforming S1
heterogenous development of clast microfabrics in diamicton layers with partitioning of deformation within matrix of diamicton
variable rotation of granule to pebble sized clasts due to simple shear imposed by the overriding ice
granule to pebble sized clasts locally controlling spacing of clast microfabric domains
wrapping of stratification and lamination around larger clasts due to simple shear and pure shear (loading) imposed by the overlying ice



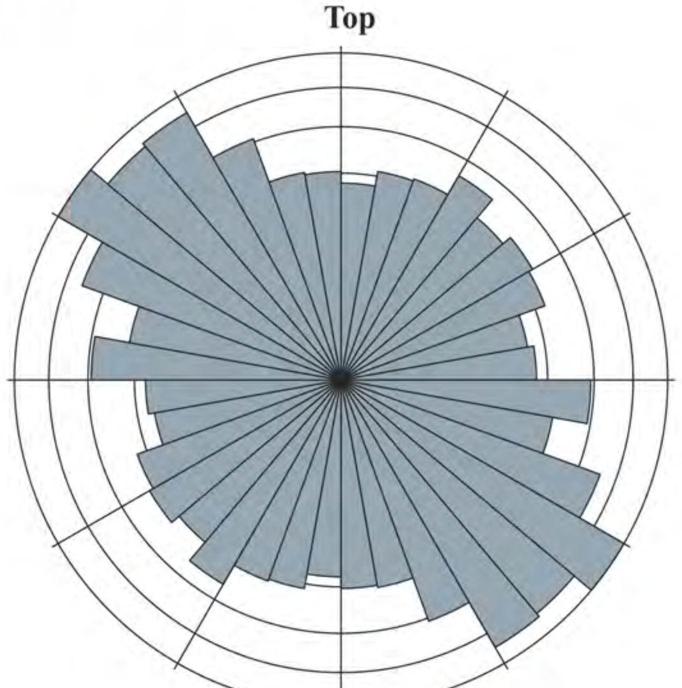
Inverness
study area
Scotland
Edinburgh
England &
Wales
Moray Firth
Moray Firth Ice Stream
Findhorn
Cloddymoss
Easterton Farm
Forres
Nairn
Cothall
Meads of St John
'stream'
Darnaway
Forest
Dalcharn
Riereach Burn
River Findhorn
Drynachan Burn
Lochindorb
5 km
N
ice movement direction



Sample N7129: Riereach Burn



Sample N7129: Riereach Burn



sample N7129 (N = 2214)

microclast fabric defined by clast long axes

axial traces of folds deforming earlier formed S1 clast microfabric

axial surfaces of crenulations/microfolds

arcuate to linear grain aggregates

patchily developed boundary between dark and pale matrix

trace of folds deforming earlier formed S1 clast microfabric

domains defining the S1 microfabric (oldest)

domains defining the S2 microfabric

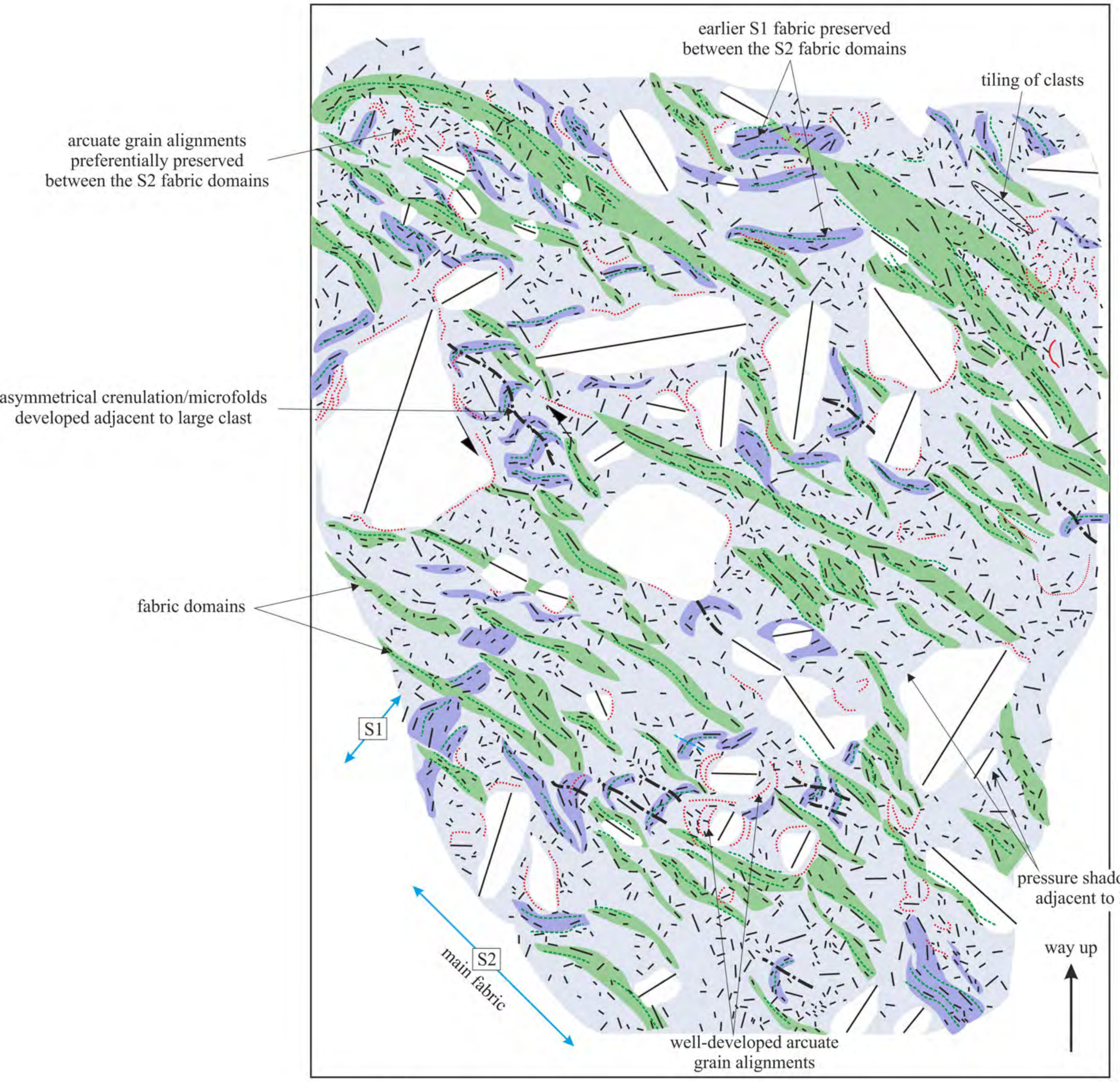
domains defining the S3 microfabric (youngest)

S1 to n relative age of fabric(s)

long axis of clasts

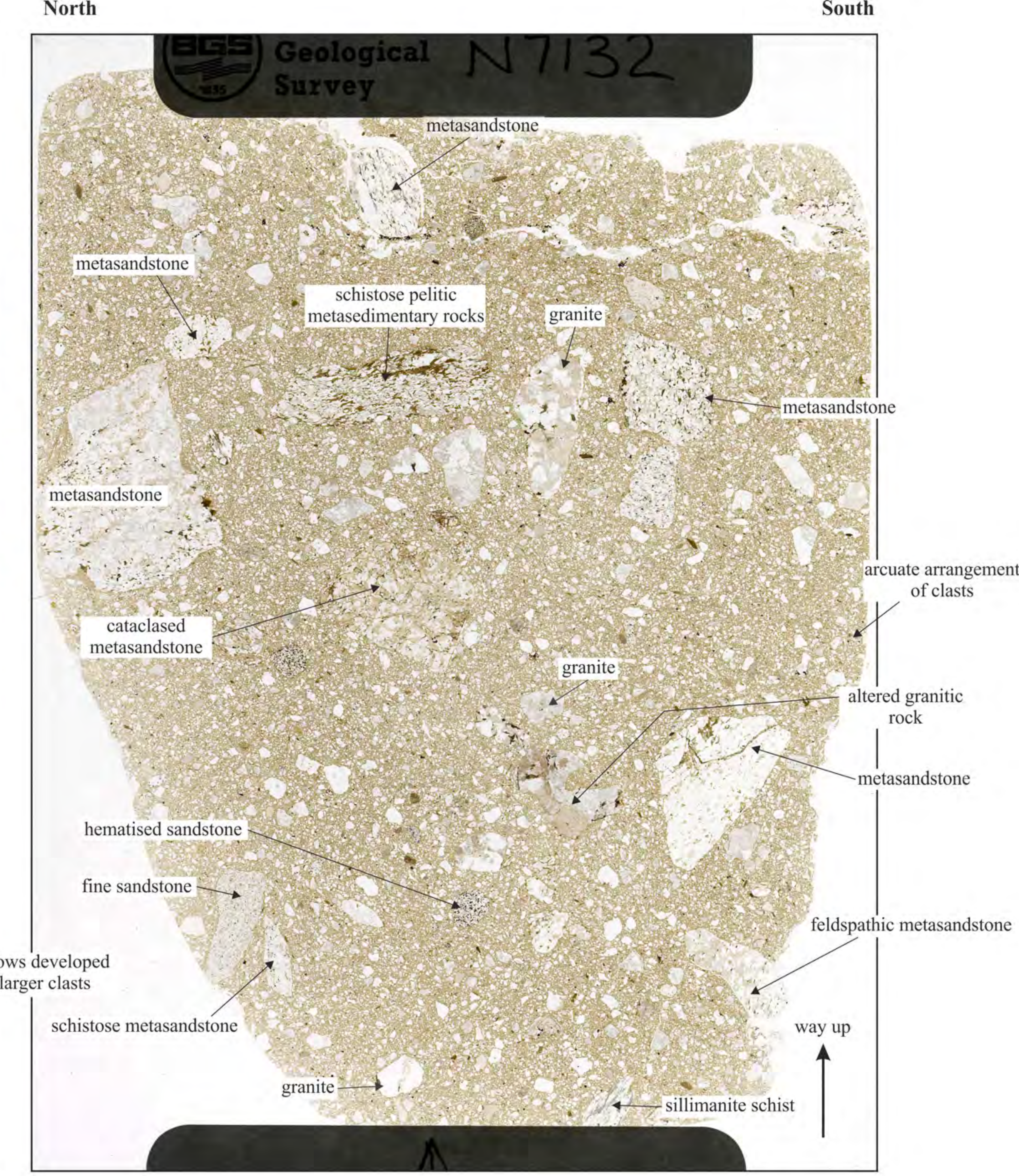
sense of shear

orientation of fabric(s)



Sample N7132: Riereach Burn

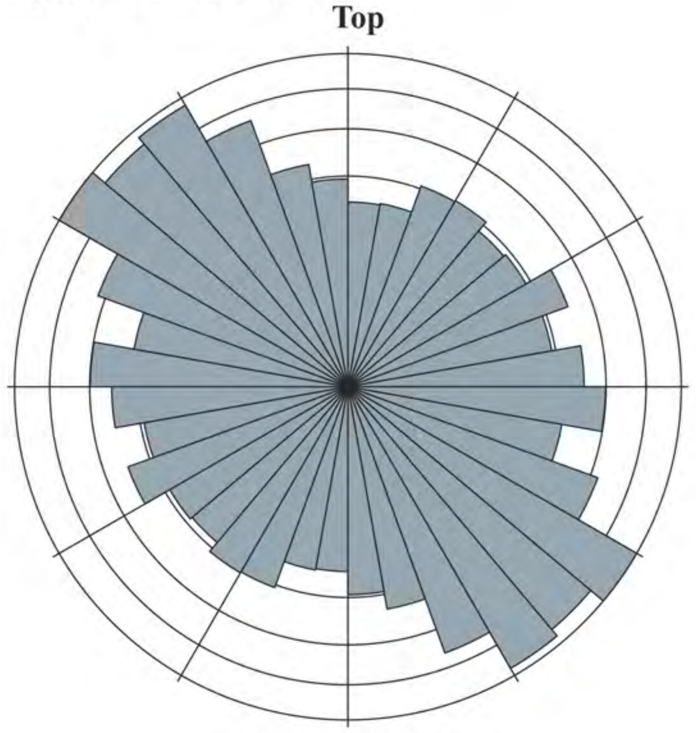
10 mm



Sample N7132: Riereach Burn

10 mm

Top

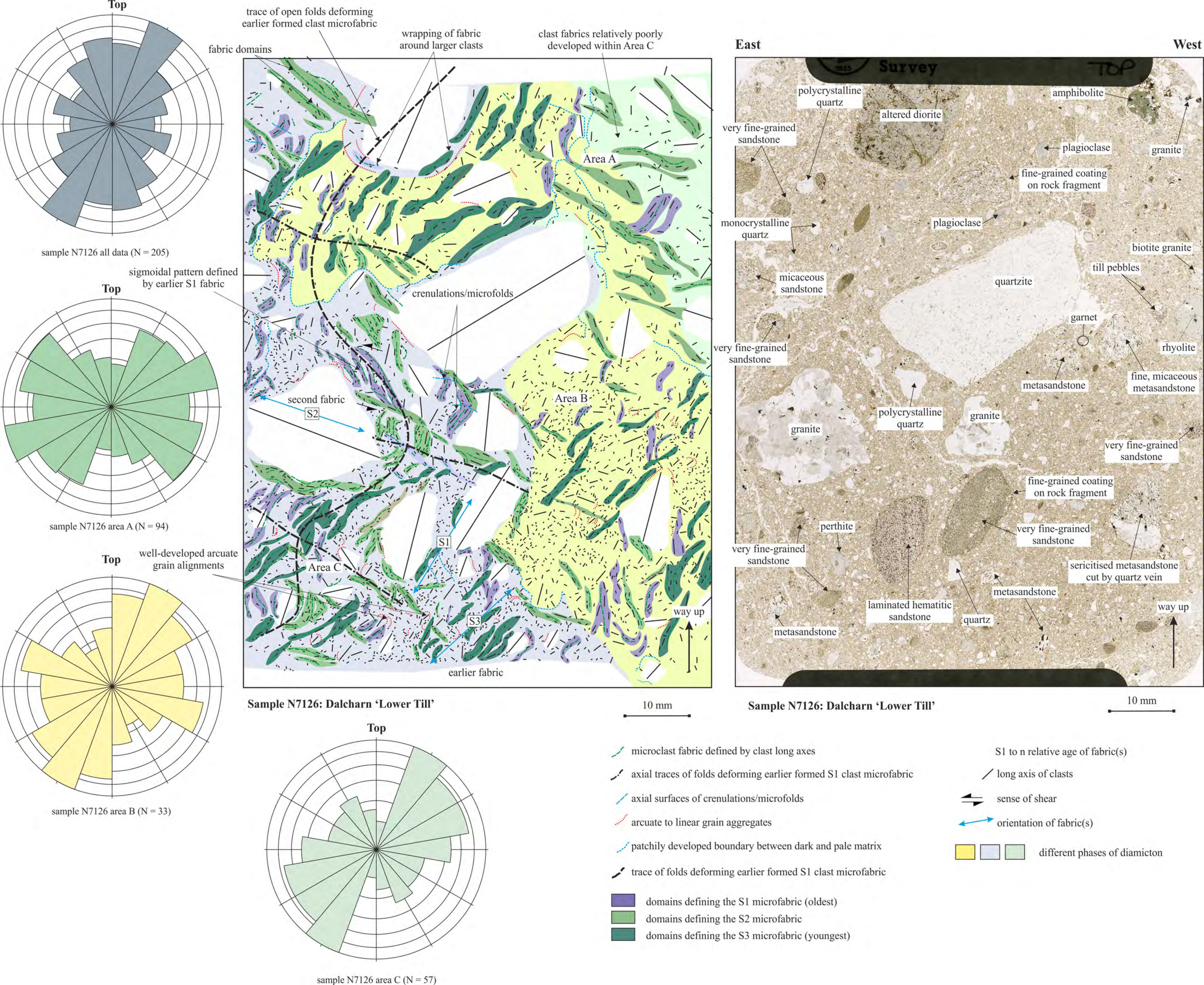


sample N7132 (N = 2233)

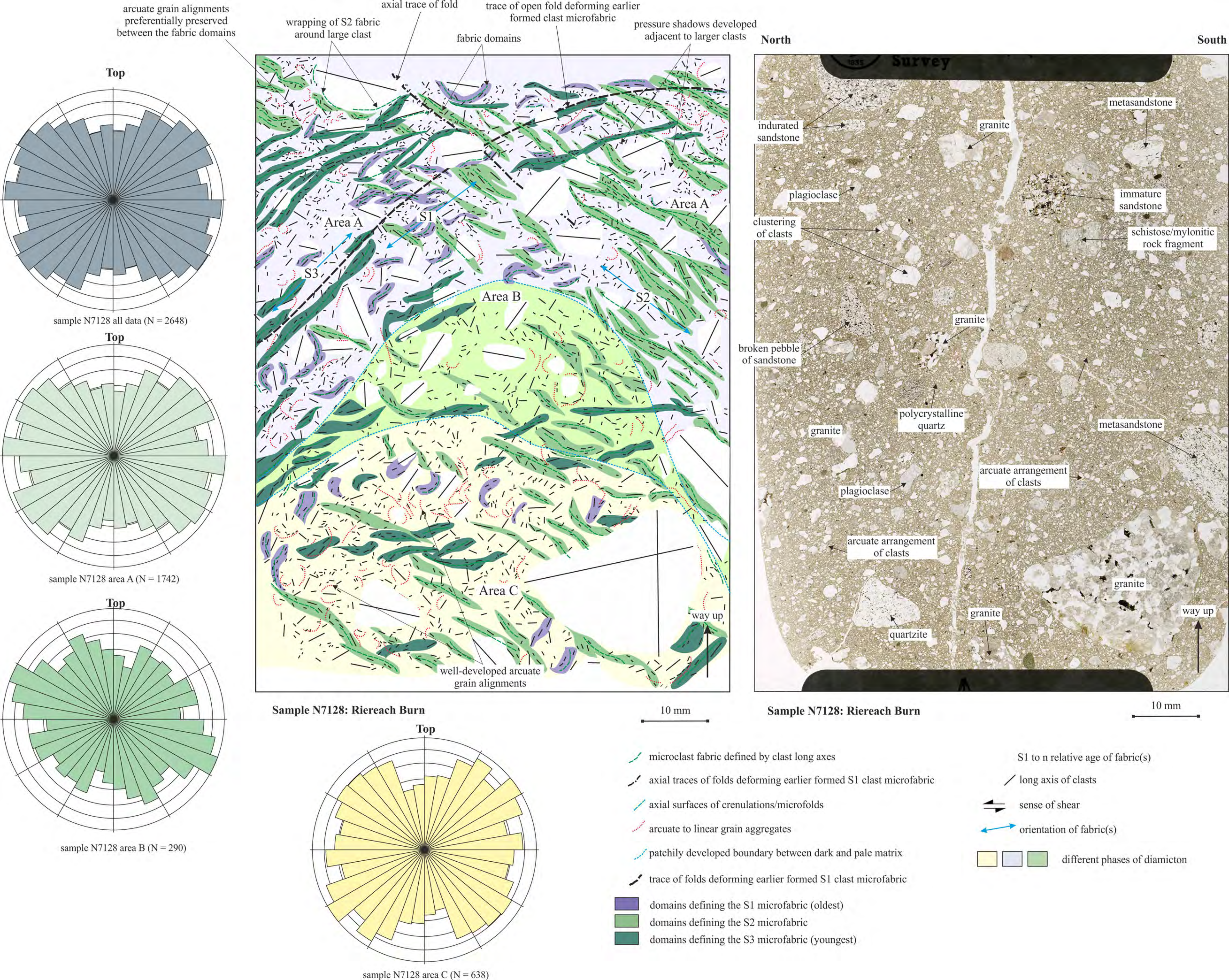
- microclast fabric defined by clast long axes
- axial traces of folds deforming earlier formed S1 clast microfabric
- axial surfaces of crenulations/microfolds
- arcuate to linear grain aggregates
- patchily developed boundary between dark and pale matrix
- trace of folds deforming earlier formed S1 clast microfabric
- domains defining the S1 microfabric (oldest)
- domains defining the S2 microfabric
- domains defining the S3 microfabric (youngest)

S1 to n relative age of fabric(s)

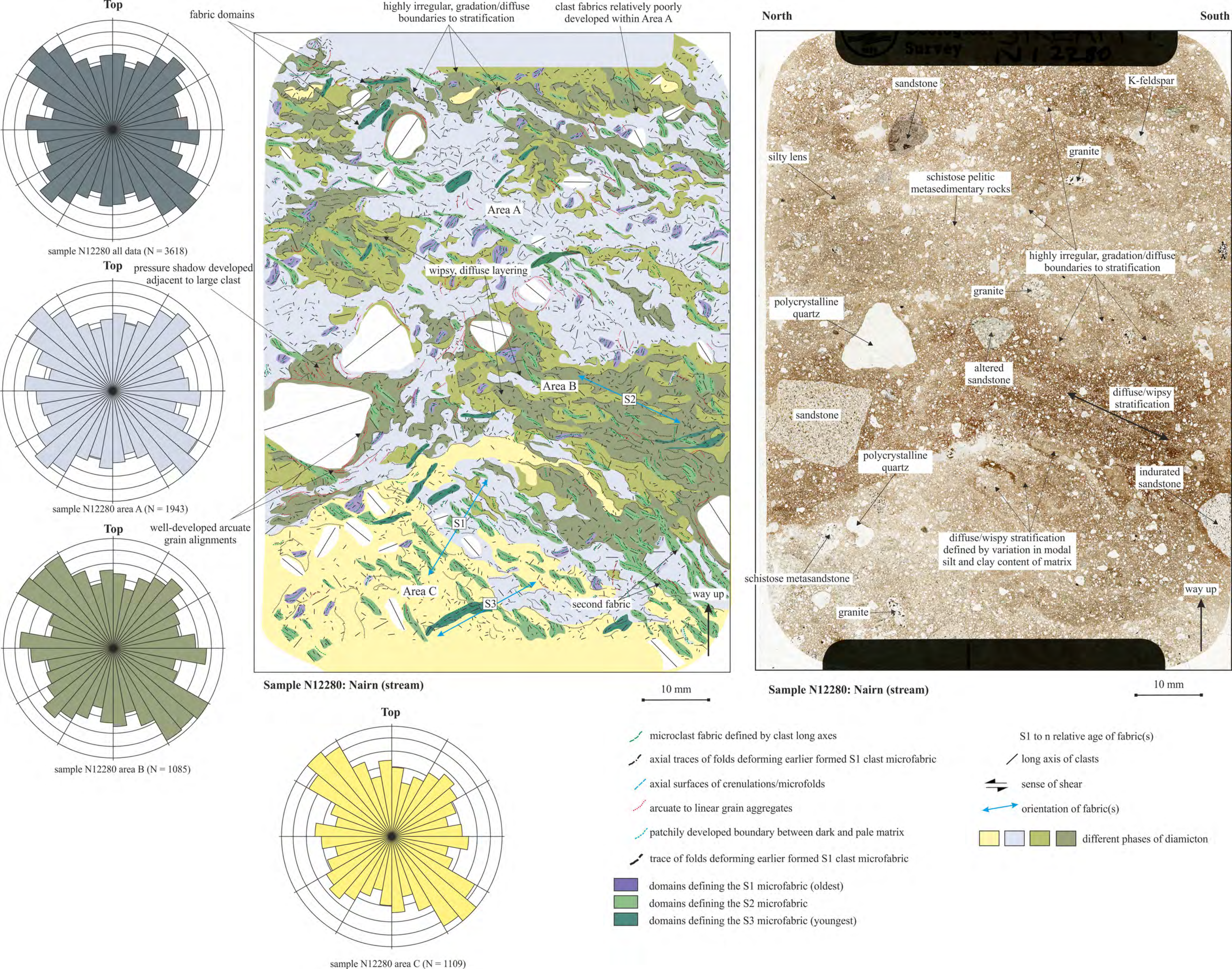
- long axis of clasts
- sense of shear
- orientation of fabric(s)



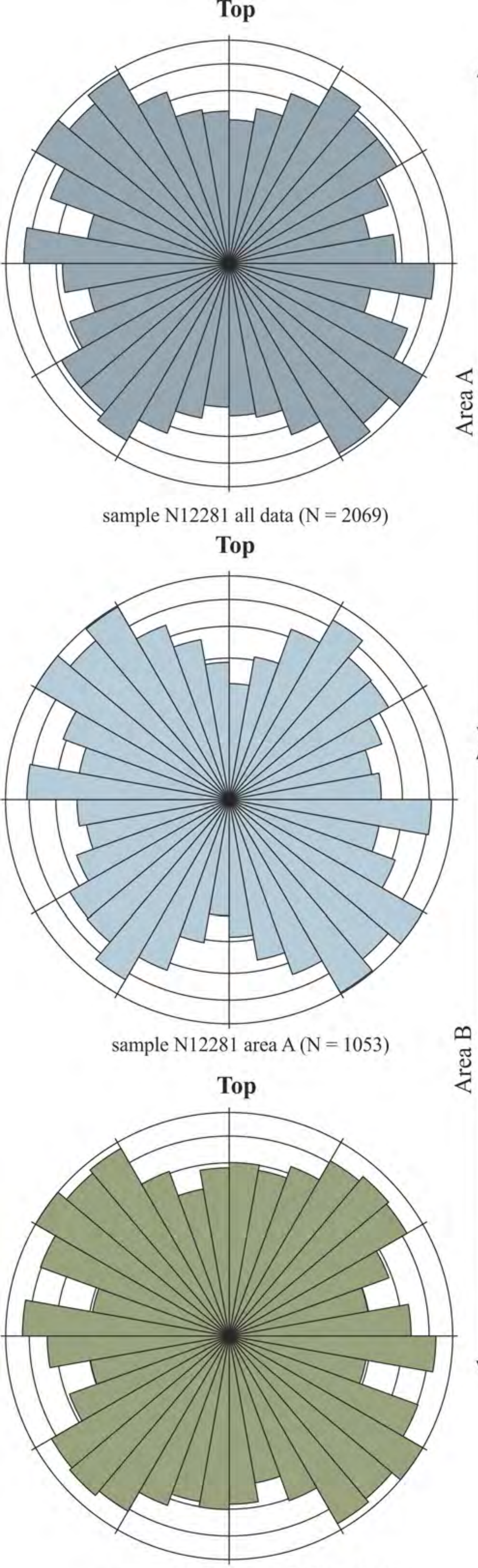
Top
sample N7126 all data (N = 205)
Top
sample N7126 area A (N = 94)
Top
sample N7126 area B (N = 33)
Top
sample N7126 area C (N = 57)
trace of open folds deforming earlier formed clast microfabric
fabric domains
wrapping of fabric around larger clasts
clast fabrics relatively poorly developed within Area C
Area A
sigmoidal pattern defined by earlier S1 fabric
crenulations/microfolds
second fabric
S2
Area B
S1
well-developed arcuate grain alignments
Area C
S3
earlier fabric
way up
Sample N7126: Dalcharn 'Lower Till'
10 mm
East
West
Survey
TOP
polycrystalline quartz
altered diorite
amphibolite
granite
very fine-grained sandstone
plagioclase
fine-grained coating on rock fragment
monocrystalline quartz
plagioclase
biotite granite
till pebbles
micaceous sandstone
quartzite
garnet
very fine-grained sandstone
rhyolite
fine, micaceous metasandstone
metasandstone
polycrystalline quartz
granite
granite
very fine-grained sandstone
fine-grained coating on rock fragment
perthite
very fine-grained sandstone
very fine-grained sandstone
sericitised metasandstone cut by quartz vein
metasandstone
laminated hematitic sandstone
quartz
metasandstone
way up
Sample N7126: Dalcharn 'Lower Till'
10 mm
microclast fabric defined by clast long axes
axial traces of folds deforming earlier formed S1 clast microfabric
axial surfaces of crenulations/microfolds
arcuate to linear grain aggregates
patchily developed boundary between dark and pale matrix
trace of folds deforming earlier formed S1 clast microfabric
domains defining the S1 microfabric (oldest)
domains defining the S2 microfabric
domains defining the S3 microfabric (youngest)
S1 to n relative age of fabric(s)
long axis of clasts
sense of shear
orientation of fabric(s)
different phases of diamicton

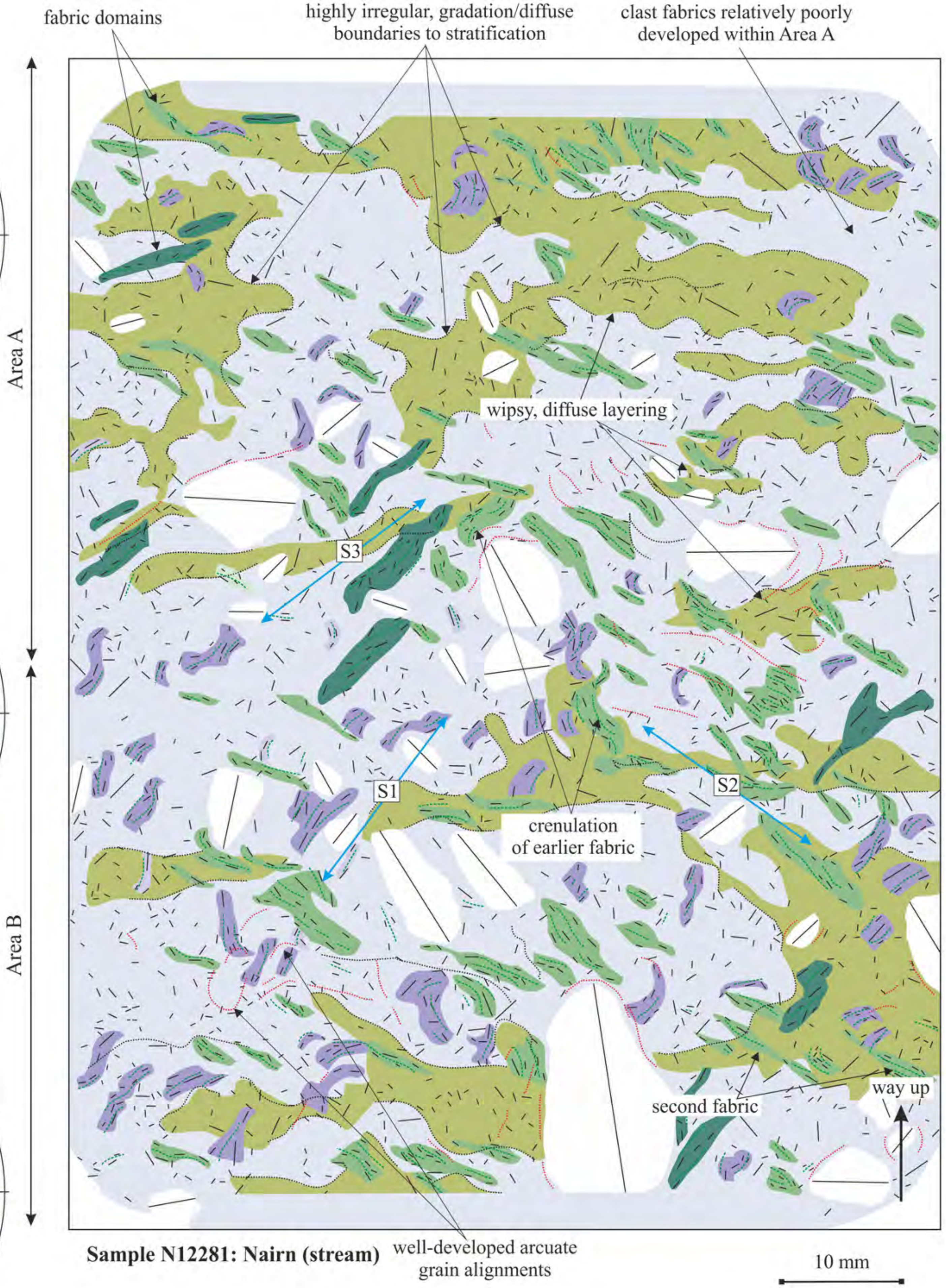


Top
sample N7128 all data (N = 2648)
Top
sample N7128 area A (N = 1742)
Top
sample N7128 area B (N = 290)
Top
sample N7128 area C (N = 638)
arcuate grain alignments preferentially preserved between the fabric domains
wrapping of S2 fabric around large clast
axial trace of fold
fabric domains
trace of open fold deforming earlier formed clast microfabric
pressure shadows developed adjacent to larger clasts
Area A
S1
Area A
S3
Area B
S2
Area C
way up
well-developed arcuate grain alignments
Sample N7128: Riereach Burn
10 mm
North
South
Survey
indurated sandstone
granite
metasandstone
plagioclase
immature sandstone
clustering of clasts
schistose/mylonitic rock fragment
granite
broken pebble of sandstone
polycrystalline quartz
granite
metasandstone
arcuate arrangement of clasts
plagioclase
arcuate arrangement of clasts
granite
quartzite
granite
way up
Sample N7128: Riereach Burn
10 mm
microclast fabric defined by clast long axes
axial traces of folds deforming earlier formed S1 clast microfabric
axial surfaces of crenulations/microfolds
arcuate to linear grain aggregates
patchily developed boundary between dark and pale matrix
trace of folds deforming earlier formed S1 clast microfabric
domains defining the S1 microfabric (oldest)
domains defining the S2 microfabric
domains defining the S3 microfabric (youngest)
S1 to n relative age of fabric(s)
long axis of clasts
sense of shear
orientation of fabric(s)
different phases of diamicton

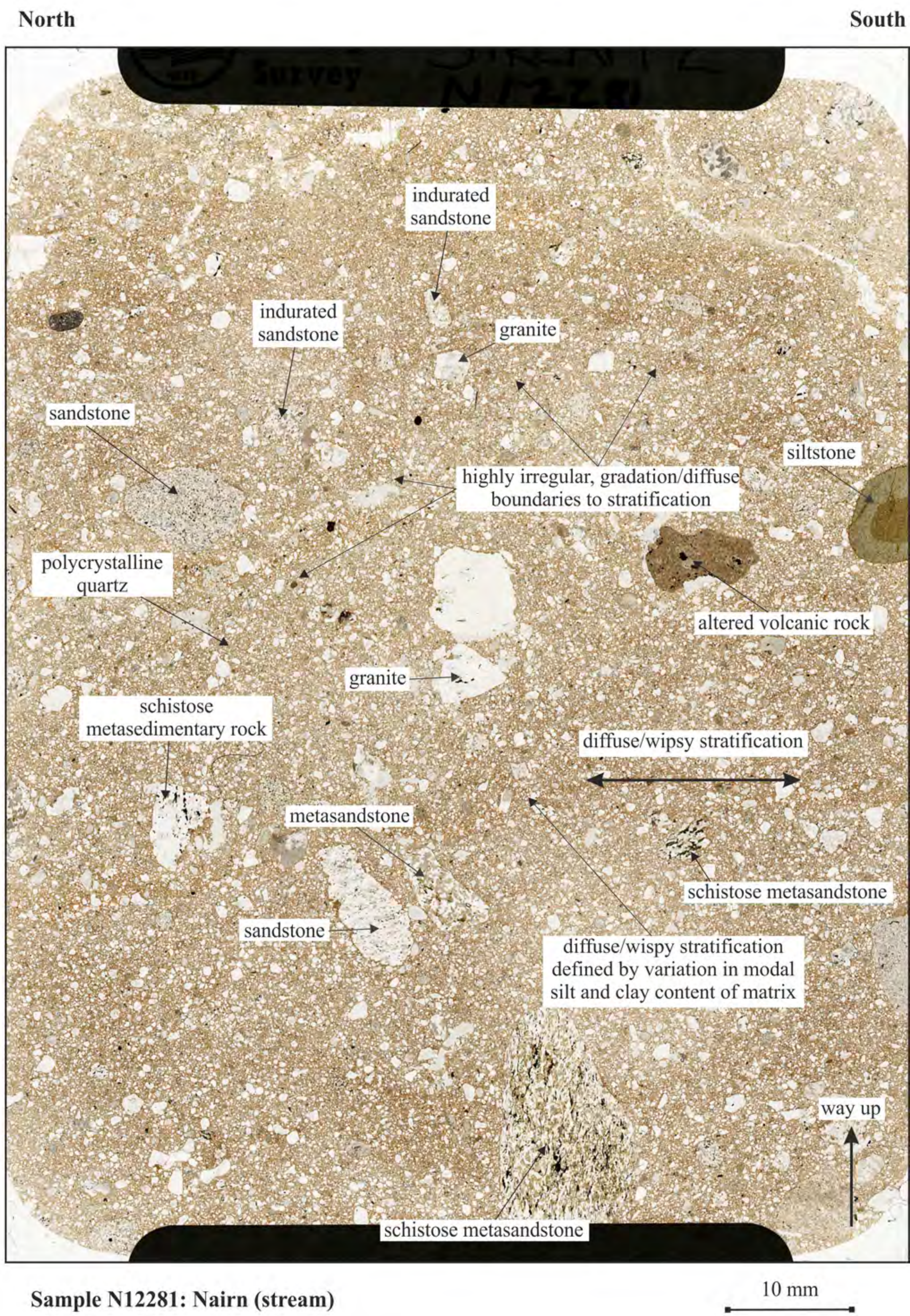


Top
fabric domains
sample N12280 all data (N = 3618)
Top
pressure shadow developed adjacent to large clast
sample N12280 area A (N = 1943)
Top
well-developed arcuate grain alignments
sample N12280 area B (N = 1085)
highly irregular, gradation/diffuse boundaries to stratification
clast fabrics relatively poorly developed within Area A
Area A
wipsy, diffuse layering
Area B
S2
S1
Area C
S3
second fabric
way up
Sample N12280: Nairn (stream)
10 mm
North
South
sandstone
K-feldspar
silty lens
granite
schistose pelitic metasedimentary rocks
highly irregular, gradation/diffuse boundaries to stratification
granite
polycrystalline quartz
altered sandstone
diffuse/wipsy stratification
sandstone
polycrystalline quartz
indurated sandstone
diffuse/wispy stratification defined by variation in modal silt and clay content of matrix
schistose metasandstone
granite
way up
Sample N12280: Nairn (stream)
10 mm
Top
sample N12280 area C (N = 1109)
microclast fabric defined by clast long axes
axial traces of folds deforming earlier formed S1 clast microfabric
axial surfaces of crenulations/microfolds
arcuate to linear grain aggregates
patchily developed boundary between dark and pale matrix
trace of folds deforming earlier formed S1 clast microfabric
domains defining the S1 microfabric (oldest)
domains defining the S2 microfabric
domains defining the S3 microfabric (youngest)
S1 to n relative age of fabric(s)
long axis of clasts
sense of shear
orientation of fabric(s)
different phases of diamicton





Sample N12281: Nairn (stream)

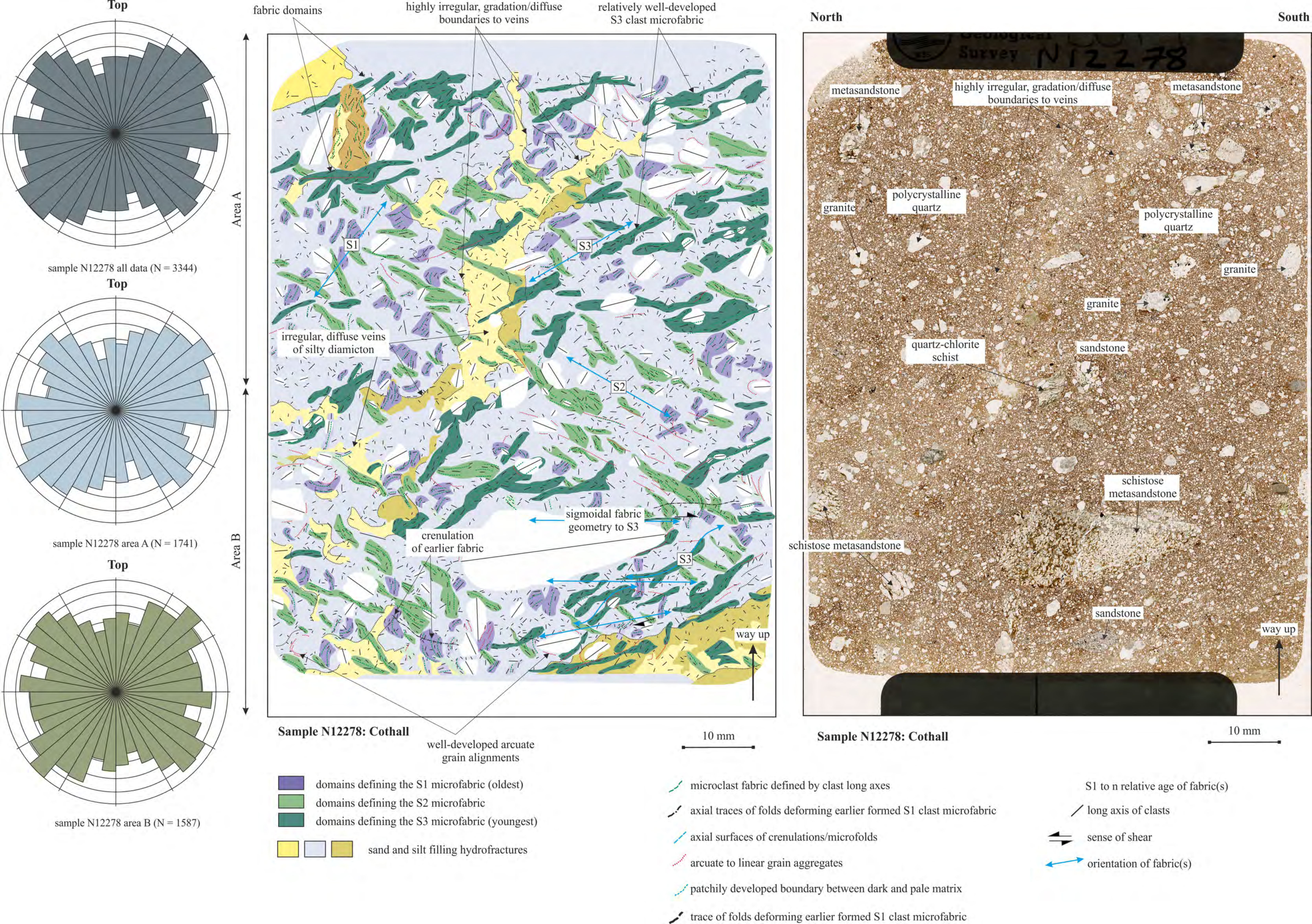


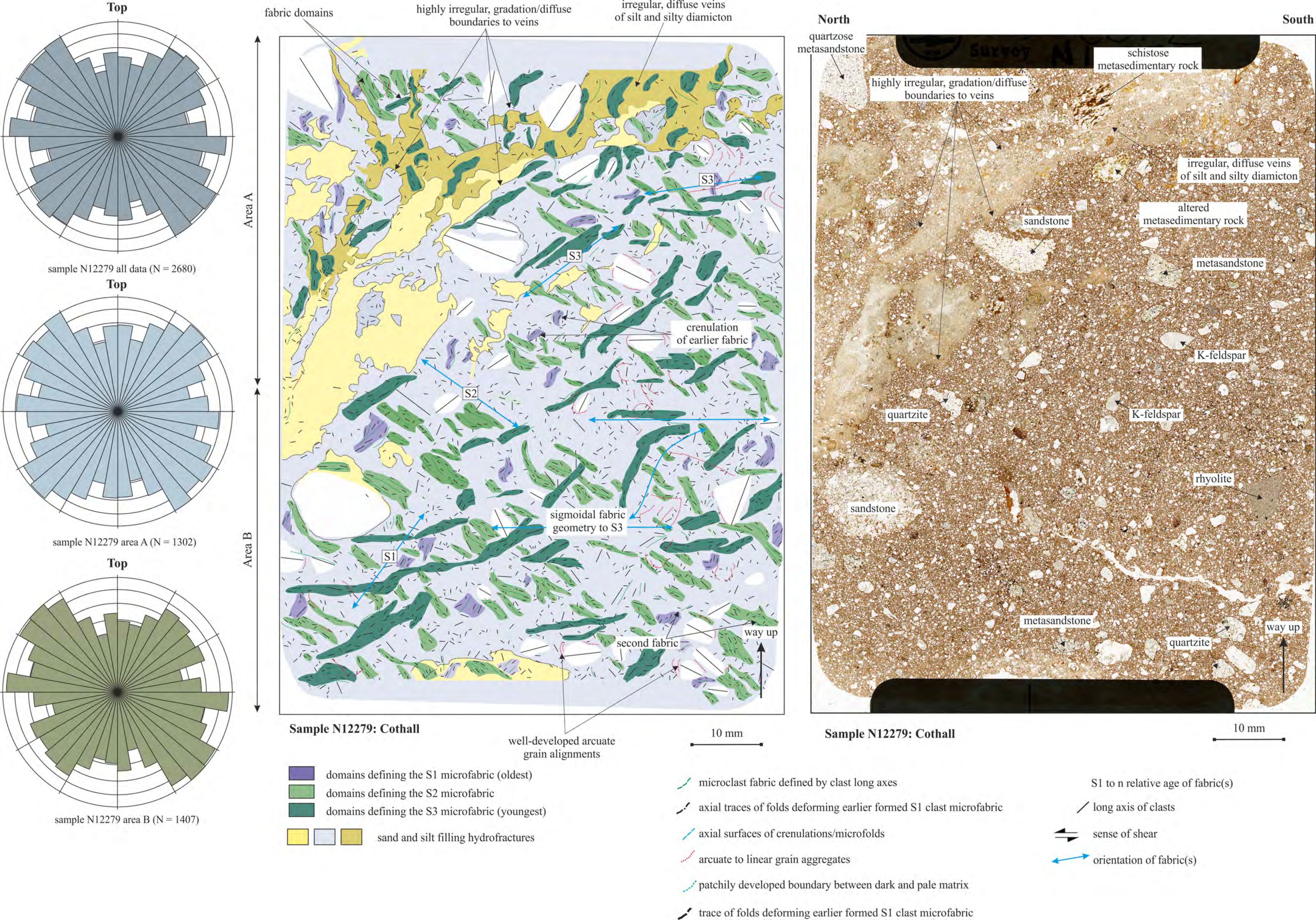
Sample N12281: Nairn (stream)

domains defining the S1 microfabric (oldest)
domains defining the S2 microfabric
domains defining the S3 microfabric (youngest)
different phases of diamicton

microclast fabric defined by clast long axes
axial traces of folds deforming earlier formed S1 clast microfabric
axial surfaces of crenulations/microfolds
arcuate to linear grain aggregates
patchily developed boundary between dark and pale matrix
trace of folds deforming earlier formed S1 clast microfabric

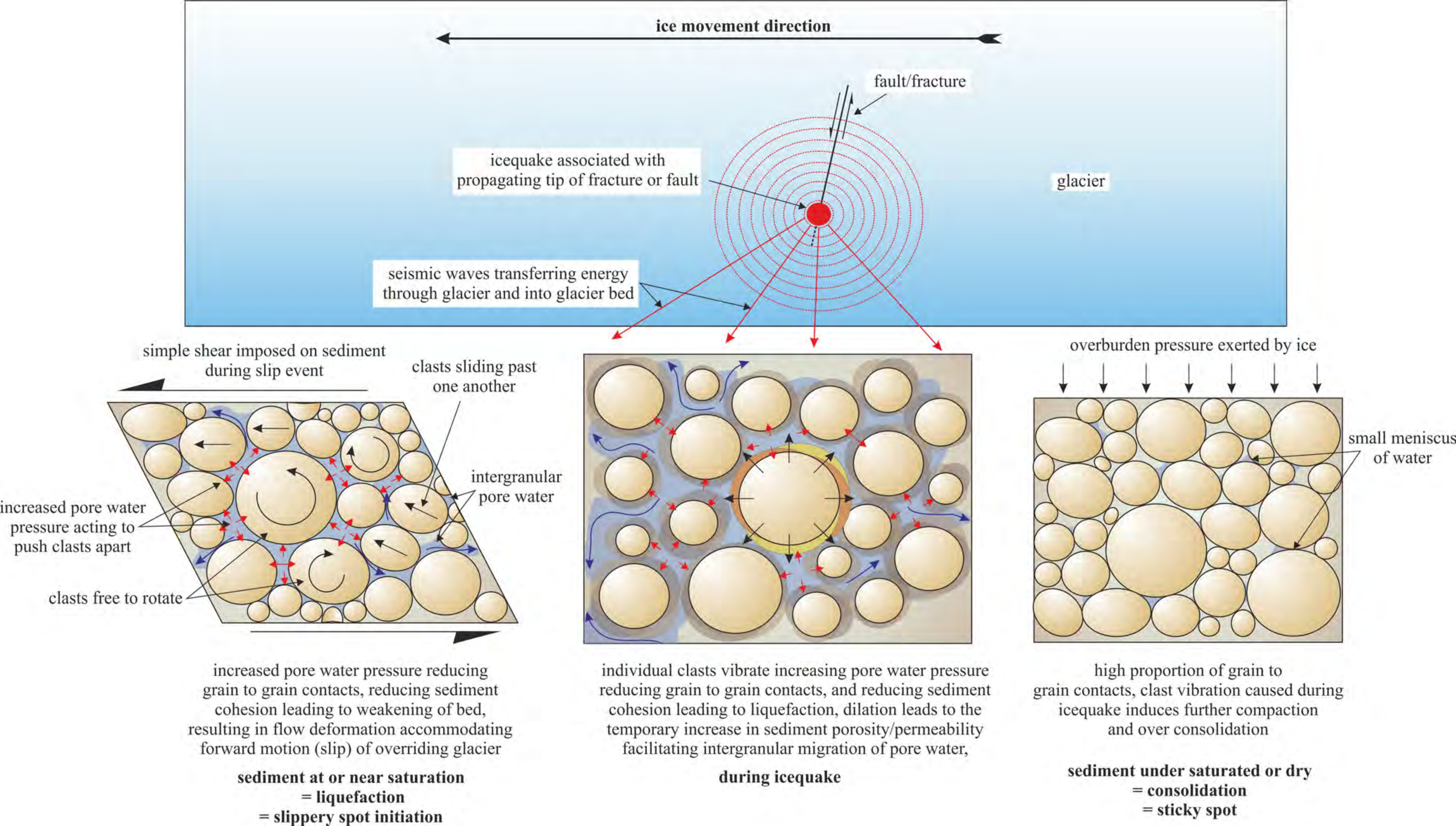
S1 to n relative age of fabric(s)
long axis of clasts
sense of shear
orientation of fabric(s)


Top
sample N12278 all data (N = 3344)
Top
sample N12278 area A (N = 1741)
Top
sample N12278 area B (N = 1587)
Area A
Area B
fabric domains
highly irregular, gradation/diffuse boundaries to veins
relatively well-developed S3 clast microfabric
S1
S3
S2
irregular, diffuse veins of silty diamicton
sigmoidal fabric geometry to S3
crenulation of earlier fabric
S3
way up
Sample N12278: Cothall
well-developed arcuate grain alignments
10 mm
North
South
metasandstone
highly irregular, gradation/diffuse boundaries to veins
metasandstone
granite
polycrystalline quartz
polycrystalline quartz
granite
granite
quartz-chlorite schist
sandstone
schistose metasandstone
schistose metasandstone
sandstone
way up
Sample N12278: Cothall
10 mm
domains defining the S1 microfabric (oldest)
domains defining the S2 microfabric
domains defining the S3 microfabric (youngest)
sand and silt filling hydrofractures
microclast fabric defined by clast long axes
axial traces of folds deforming earlier formed S1 clast microfabric
axial surfaces of crenulations/microfolds
arcuate to linear grain aggregates
patchily developed boundary between dark and pale matrix
trace of folds deforming earlier formed S1 clast microfabric
S1 to n relative age of fabric(s)
long axis of clasts
sense of shear
orientation of fabric(s)

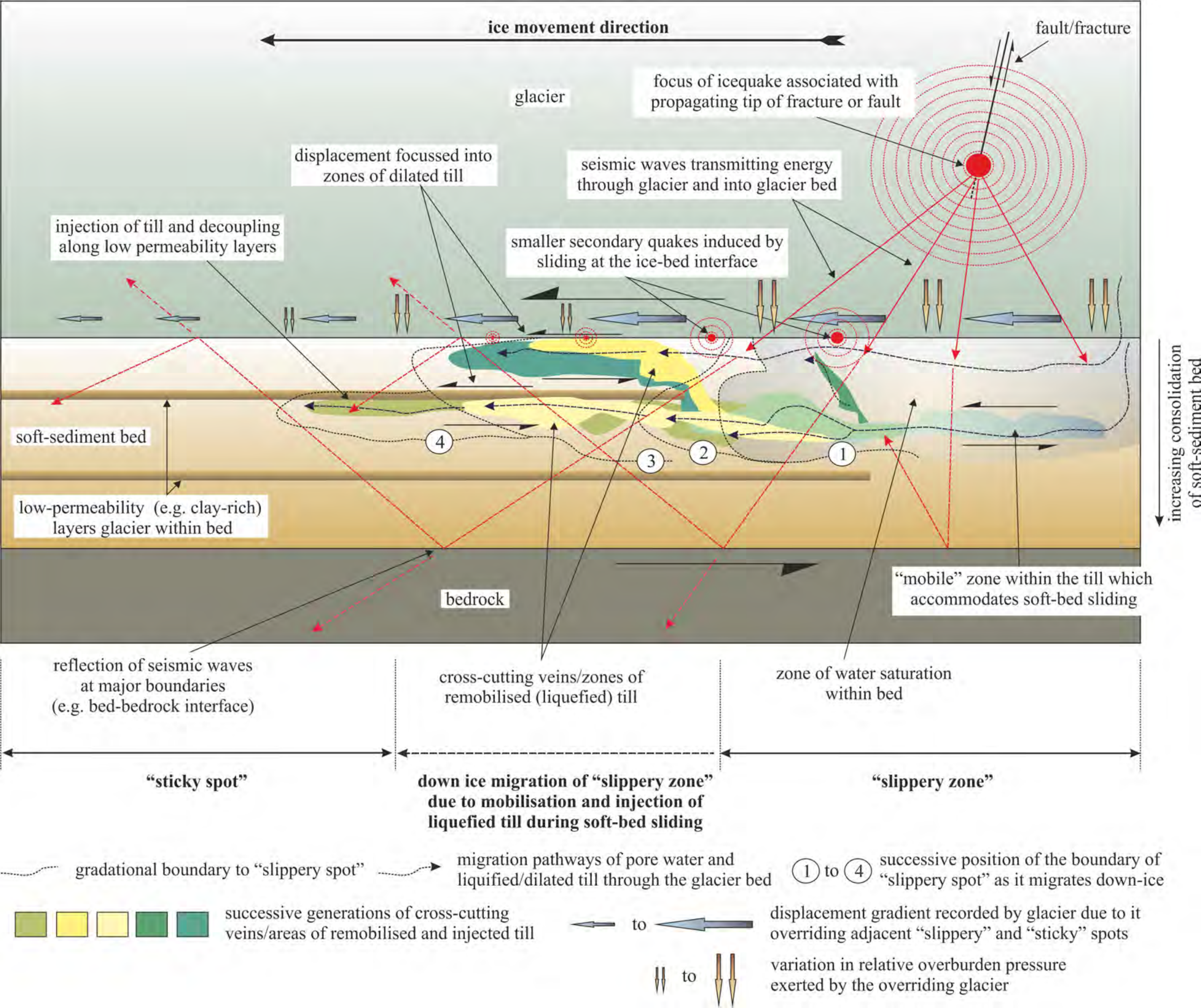


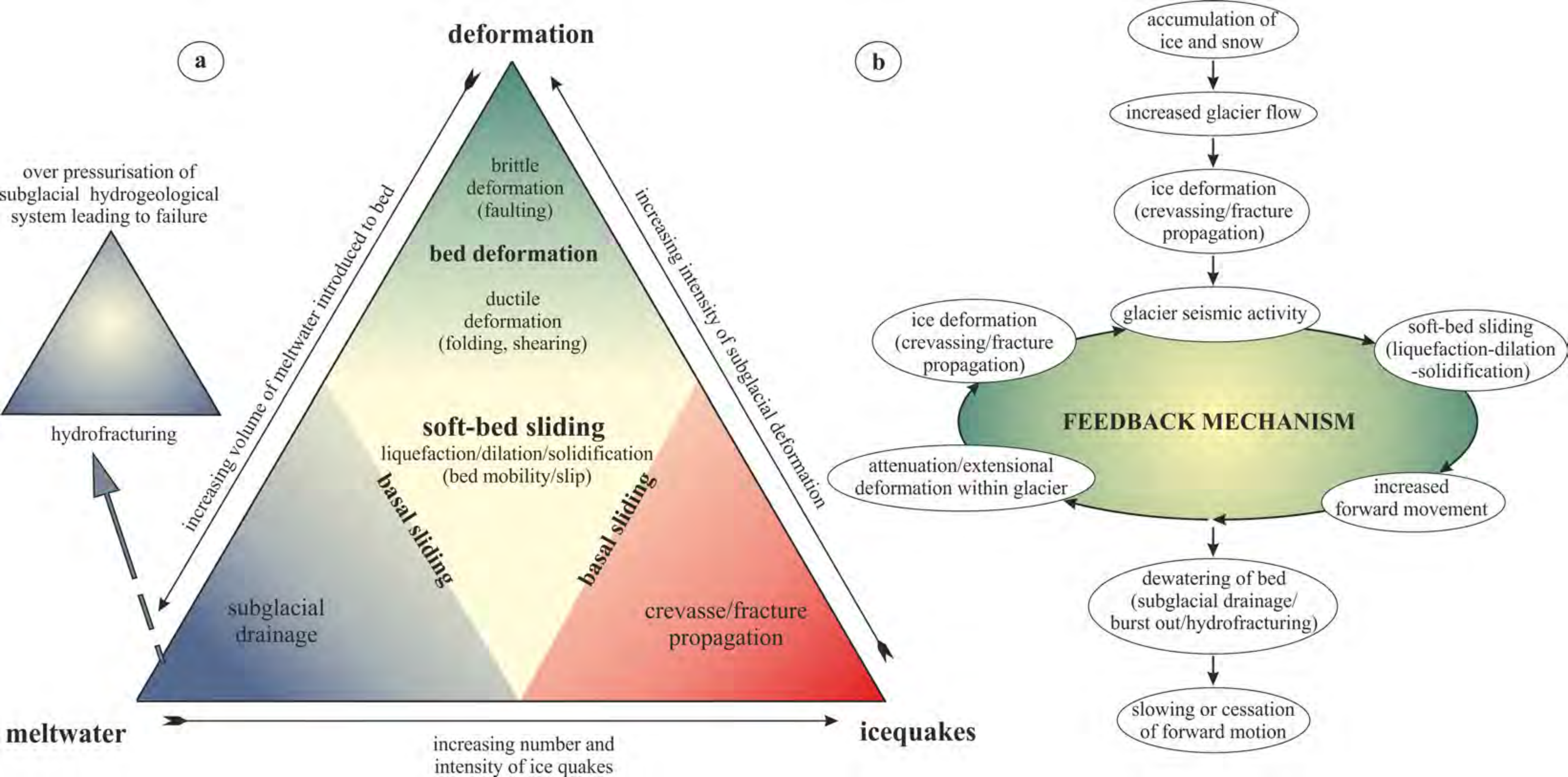
Top
sample N12279 all data (N = 2680)
Top
sample N12279 area A (N = 1302)
Top
sample N12279 area B (N = 1407)
Area A
Area B
fabric domains
highly irregular, gradation/diffuse boundaries to veins
irregular, diffuse veins of silt and silty diamicton
S3
S3
crenulation of earlier fabric
S2
S1
sigmoidal fabric geometry to S3
second fabric
way up
well-developed arcuate grain alignments
Sample N12279: Cothall
10 mm
North
South
quartzose metasandstone
highly irregular, gradation/diffuse boundaries to veins
schistose metasedimentary rock
irregular, diffuse veins of silt and silty diamicton
sandstone
altered metasedimentary rock
metasandstone
K-feldspar
quartzite
K-feldspar
rhyolite
sandstone
metasandstone
quartzite
way up
Sample N12279: Cothall
10 mm
domains defining the S1 microfabric (oldest)
domains defining the S2 microfabric
domains defining the S3 microfabric (youngest)
sand and silt filling hydrofractures
microclast fabric defined by clast long axes
axial traces of folds deforming earlier formed S1 clast microfabric
axial surfaces of crenulations/microfolds
arcuate to linear grain aggregates
patchily developed boundary between dark and pale matrix
trace of folds deforming earlier formed S1 clast microfabric
S1 to n relative age of fabric(s)
long axis of clasts
sense of shear
orientation of fabric(s)

Glacier ice
movement direction of overriding glacier
base of overriding glacier ice
Basal Sliding Zone (laminated till) composed of alternating layers of sandy diamicton and laminated silt and clay
Basal gravelly diamicton
wrapping of foliation around pebble
crenulation adjacent to rotated clast
crenulation of laminated silt and clay adjacent to rotated clast
overturned lamination
recumbent fold
calcareous, matrix-supported, pebbly sandy diamicton
folding/crenulation of lamination due to rotation of clasts
lenticular to eye-shaped "till pebbles"
folding of layering around pebble
thin, irregular silt and clay layers
irregular veins/layers of sandy diamicton
vein of diamicton cross-cutting lamination
disruption of diamicton during or immediately after injection to form irregular 'till' pebbles
recumbent folds deforming laminated silt and clay
irregular to rounded 'till' pebbles
highly irregular, complex boundaries to diamicton layers
massive, homogenised silt
lenticular 'till pebbles'
thrusts
truncation of lamination in silt and clay layer against diamicton
dominant clast microfabric
injection of dilated/liquefied diamicton into the zone of basal sliding
variable mixing of sandy diamicton with liquefied and remobilised silt and clay to form a diamicton with a darker matrix
prominent silt and clay layer
crenulation of earlier formed (S1) clast microfabric
way up
Sample R.164
Sample R.163A
Sample R.163B
Sample R.163C
Sample R.163D
Sample R.248
Sample R.166
rotated clasts
isoclinal folding within silt and clay layer
laminated, calcareous silt and clay
asymmetrical fabric geometry recording a sense of shear
asymmetrical pressure shadows on 'till pebble'
rootless, intrafolial folds within laminated silt and clay
irregular, "involved" boundaries to diamicton layers/veins
deformation adjacent to large clast
rotation of clasts in response to simple shear
irregular, involved boundaries to diamicton layers
variably rounded clasts reworked from underlying gravelly diamicton
liquefaction and remobilisation of silt-rich layers
pebbly 'vinaigrette' textured, calcareous, matrix-supported, pebbly sandy to clayey diamicton
zone of subvertical, irregular microfabric domains associated with upward migration of liquefied diamicton
preferred shape alignment of granule to pebble sized clasts
preferred alignment of granule and pebble sized clasts
gravelly diamicton
arcuate grain alignments around large clast
lateral variation in thickness of diamicton layers resulting in ribbon-like stratification
injection of diamicton layers parallel to lamination in host silt and clay
heterogeneous folding and thrusting of laminated silt and clay indicative of periodic coupling of the glacier with its bed
diamicton layers locally cross-cut and therefore post-date formation of the lamination, folds and faults developed within host silt and clay
heterogenous development of clast microfabrics in diamicton layers
variable rotation of granule to pebble sized clasts due to simple shear imposed by the overriding ice
clast microfabrics developed in diamicton layers coplanar with faults deforming the adjacent laminated silt and clay indicating that they formed in response to the same stress regime and that deformation was penecontemporaneous
normal and reverse graded, laminated silt and clay recording deposition from meltwater flowing along the ice-bed interface
wrapping of stratification and lamination around larger clasts due to simple shear and pure shear (loading) imposed by the overlying ice
'vinaigrette' textured diamicton resulting from partial mixing of injected diamicton with variably liquefied silt and clay
highly irregular, complex/involuted boundaries between layers consistent with high pore water conents
heterogenous development of clast microfabrics in diamicton
clast microfabrics developed in diamicton layers coplanar with faults deforming the adjacent laminated silt and clay indicating that they formed in response to the same stress regime and that deformation was penecontemporaneous
liquefaction and homogenisation of silt accompanied injection of diamicton



ice movement direction
fault/fracture
icequake associated with propagating tip of fracture or fault
glacier
seismic waves transferring energy through glacier and into glacier bed
simple shear imposed on sediment during slip event
clasts sliding past one another
intergranular pore water
increased pore water pressure acting to push clasts apart
clasts free to rotate
overburden pressure exerted by ice
small meniscus of water
increased pore water pressure reducing grain to grain contacts, reducing sediment cohesion leading to weakening of bed, resulting in flow deformation accommodating forward motion (slip) of overriding glacier
sediment at or near saturation
= liquefaction
= slippery spot initiation
individual clasts vibrate increasing pore water pressure reducing grain to grain contacts, and reducing sediment cohesion leading to liquefaction, dilation leads to the temporary increase in sediment porosity/permeability facilitating intergranular migration of pore water,
during icequake
high proportion of grain to grain contacts, clast vibration caused during icequake induces further compaction and over consolidation
sediment under saturated or dry
= consolidation
= sticky spot


ice movement direction
fault/fracture
glacier
focus of icequake associated with propagating tip of fracture or fault
displacement focussed into zones of dilated till
seismic waves transmitting energy through glacier and into glacier bed
injection of till and decoupling along low permeability layers
smaller secondary quakes induced by sliding at the ice-bed interface
soft-sediment bed
4
3
2
1
increasing consolidation of soft-sediment bed
low-permeability (e.g. clay-rich) layers glacier within bed
bedrock
"mobile" zone within the till which accommodates soft-bed sliding
reflection of seismic waves at major boundaries (e.g. bed-bedrock interface)
cross-cutting veins/zones of remobilised (liquefied) till
zone of water saturation within bed
"sticky spot"
down ice migration of "slippery zone" due to mobilisation and injection of liquefied till during soft-bed sliding
"slippery zone"
gradational boundary to "slippery spot"
migration pathways of pore water and liquified/dilated till through the glacier bed
1 to 4 successive position of the boundary of "slippery spot" as it migrates down-ice
successive generations of cross-cutting veins/areas of remobilised and injected till
to
displacement gradient recorded by glacier due to it overriding adjacent "slippery" and "sticky" spots
to
variation in relative overburden pressure exerted by the overriding glacier


a
deformation
meltwater
icequakes
over pressurisation of subglacial hydrogeological system leading to failure
hydrofracturing
increasing volume of meltwater introduced to bed
increasing intensity of subglacial deformation
increasing number and intensity of ice quakes
brittle deformation (faulting)
bed deformation
ductile deformation (folding, shearing)
soft-bed sliding
liquefaction/dilation/solidification (bed mobility/slip)
basal sliding
basal sliding
subglacial drainage
crevasse/fracture propagation
b
accumulation of ice and snow
increased glacier flow
ice deformation (crevassing/fracture propagation)
glacier seismic activity
ice deformation (crevassing/fracture propagation)
soft-bed sliding (liquefaction-dilation -solidification)
FEEDBACK MECHANISM
attenuation/extensional deformation within glacier
increased forward movement
dewatering of bed (subglacial drainage/ burst out/hydrofracturing)
slowing or cessation of forward motion

Highlights

- Subglacial traction tills undergo repeated phases of liquefaction and deformation
- This process lowers the shear strength of the till, facilitating glacier movement
- This soft-bed sliding occurs in a series of ‘stick-slip’ events
- Soft-bed sliding may be partially facilitated by glacier seismic activity